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# 3D Simulation of Hybrid Fabry-Pérot for Single Mode Fibre

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## Abstract

**3D** modal simulation of **Hybrid Fabry Pérot (H-FP)** consisting of a Bragg grating (**Bg**) and a  
10 multilayer mirror between single-mode optical fibres shows that diffraction in their multilayer is  
negligible, but that multimode **3D S-matrix** calculation is essential in the multilayer to determine the  
adequate thickness of the interface layer with the **Bg**. The single-mode approximation made in **1D**  
calculation is justified for their sinusoidal profile **Bg**, but is not at the top of the transmission peak for  
their high step profile **Bg**. The study of manufacturing constraints shows that feasible **H-FPs**, with  
15 rejection broad of several hundred nanometers, provide access to bandpass widths as low as 15 fm, but  
that the control of the bandwidth shift remains delicate for the realization of large series. The principle  
of **H-FP** with a high refraction index step reflector and a low step one is also valid for integrated  
optics. All weak spectral oscillations in the rejection band of **H-FPs** have been interpreted. Finally, the  
simulation of **H-FPs** with Interleaved Fibre (**IF**) between their 2 mirrors makes it possible to deduce  
20 also for **H-FPs** without **IF** and for some of their properties a quantitative model of equivalent cavity  
filled with homogeneous medium and with localized mirrors equidistant by a fraction of the length of  
the **Bg** depending only on its reflection coefficient. This equivalent cavity is used to evaluate the line

width. This model also applies to 2 **Bg-FPs** without **IF** with a double length of the equivalent cavity for the same grating.

## 25 **Highlights**

- Hybrid Fabry-Pérot (**H-FP**) = multilayer mirror + Bragg grating (**Bg**) = ultra-narrow bandpass and wide rejection
- **3D S-matrix-simulation** indispensable at least to determine the boundary layer with the **Bg** even despite little diffraction in the layers, and also for **Bg** having high refractive index step
- 30 • Detailed study of the transmission peak, rejection band and manufacturing tolerances of **H-FP**
- Comparison with **Bg-FP** (where both mirrors are **Bg**) and simulation of **H-FP** and **Bg-FP** with fibre between their mirrors
- Deduction of an equivalent model of the **H-FP** and **Bg-FP** explaining quantitatively their line width

## 35 **Keywords**

Narrow bandpass filter, Optical fibre, Integrated Optics, Modal Simulation, S Matrix

## **1. Introduction**

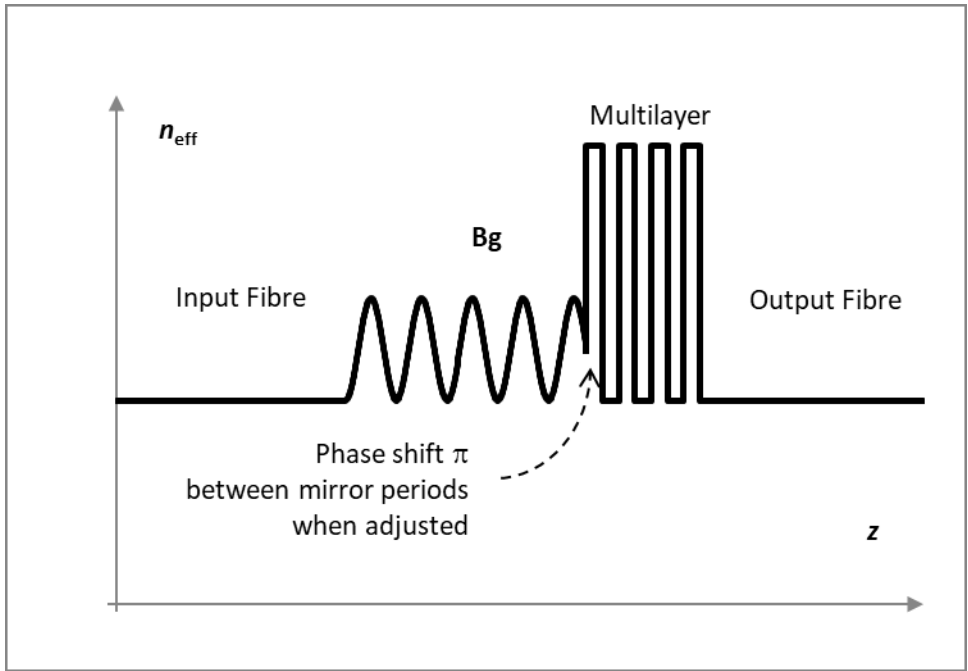
Hybrids Fabry-Pérot (**H-FP**) were introduced in [1] by **1D** numerical simulation. They consist of a multi-layer mirror of all-quarter-wave optical thickness layers located at the end of a Bragg grating  
40 (**Bg**) embedded in an optical fibre, for example, so that at the interface, the periods of the grating and the multi-layer are in phase opposition (fig.1a). The interest of **H-FP** presented in [1] is to obtain a bandpass filter a few pm wide in a rejection band several hundred nanometers wide, simultaneously obtaining the advantages of **FP** with 2 Bragg mirrors (**Bg-FP**) and Multilayer fibred **FP** (**M-FP**) without their disadvantages. In [1], phase opposition was obtained by an additional photosensitization

45 of any distribution, but whose overall intensity was adjusted in the axial direction, at the interface  
between the multilayer glued onto the cleaved **Bg**. Serial multiple **H-FPs** were also simulated in [1].  
Have been simulated in [2] very narrow 2-band **H-FPs** called "bicornes", and in [3], "chirped" **Bg-H-**  
**FPs** (with pseudo-periodic **Bg**'s whose period varies for example linearly along the optical axis  $z$ ). A  
**H-FP** with phase opposition adjustment during the multilayer deposition by adjusting the thickness of  
50 its boundary layer with the end of the cleaved **Bg** was then experimentally performed with a 100 pm  
passband [4, 5]. Finally, in [6], a **H-FP** was performed by adjusting the phase opposition by polishing  
adjusting the millimetre to sub-millimetre length of interleaved fibre (**IF**) between a photo-recorded  
**Bg** in a cleaved fibre beyond the photo-recording, and a multi-layer mirror deposited at the end of  
another fibre (the whole being maintained in a ferrule), getting so an **IF-H-FP** with 9 pm passband in  
55 a 400 nm rejection band. This amounts to considering in addition a section of fibre interleaved  
between the multilayer and the **Bg** of figure 1a as in figure 1b.

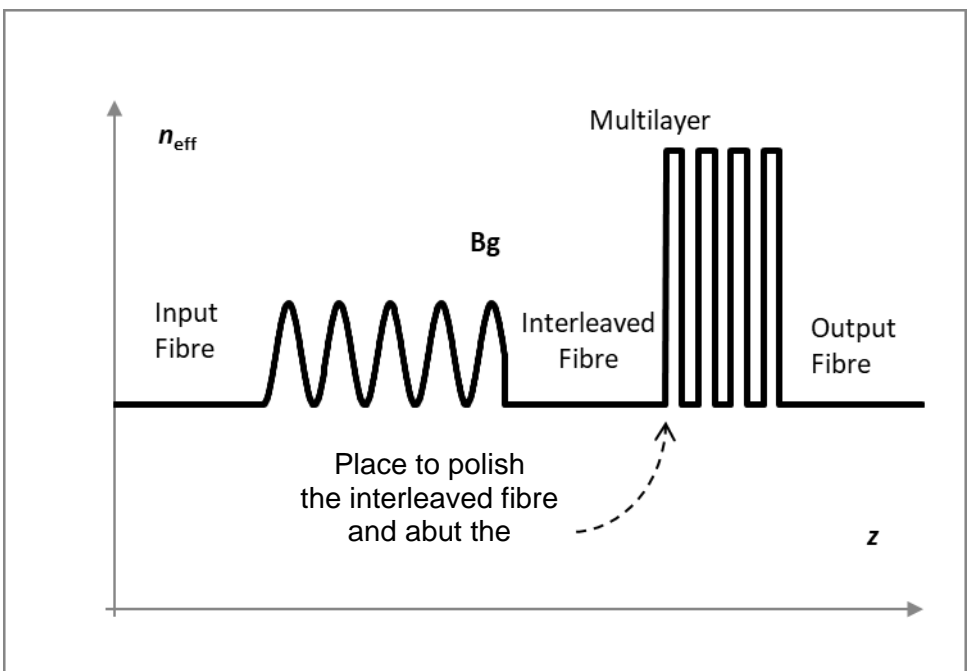
The **1D** calculations made in [1] were based on certain assumptions:

- Single-mode propagation throughout the **Bg** of the **H-FP** in the direction of propagation  $z$
- In the case of a **Bg** where the core refractive index  $n_{co}(z)$  and the optical cladding index  $n_{cl}(z)$   
60 vary sinusoidally, sinusoidal variation of the effective index of the fundamental mode  $n_{eff}(z)$
- Propagation of a plane wave orthogonal to the layers through the **H-FP** multilayer, with in  
particular no diffraction

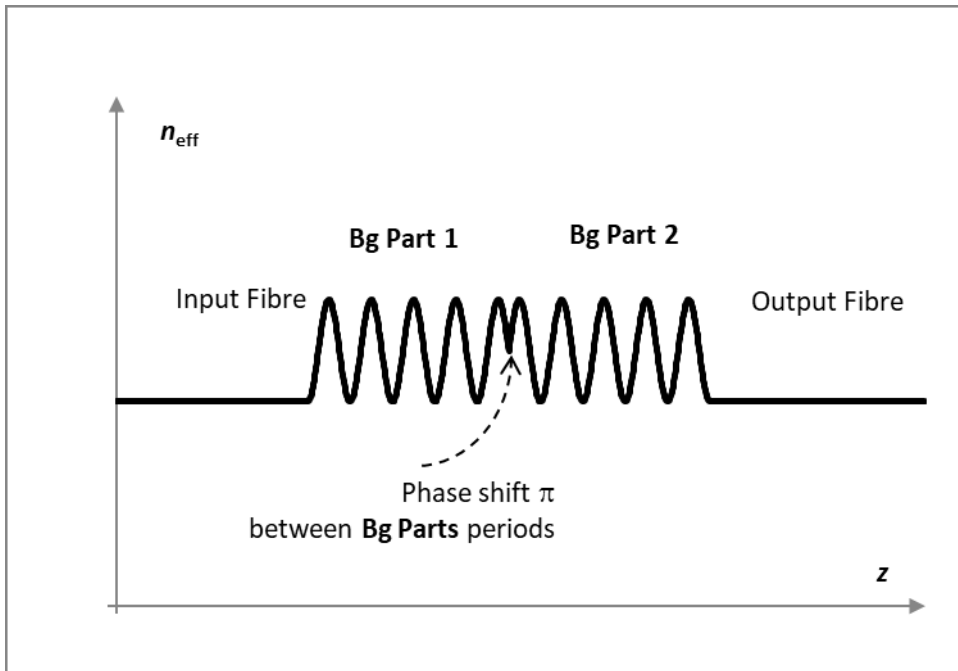
Thus, Bragg gratings were simulated in **1D** using the characteristic matrix method [7, 8] as multilayers  
having as refractive indices the effective indices of the fundamental mode in each sample of the Bragg  
65 grating period.



**Figure 1.a:** Schematic diagram of **H-FP**. Note the phase shift between the **Bg** period and the multilayer mirror period appearing at a certain  $z$ -position. In the simulations of [1, 2, 3], this position is any, and the phase between the two periods is adjusted by UV photo-refraction applied to the whole **H-FP**. In [4, 5], this position and so the phase, are adjusted by accurately controlling the thickness of the interface layer of the multilayer with the **Bg**. The representation in this diagram is not to scale.



75 **Figure 1.b:** Schematic diagram of an **IF-H-FP** constructed in [6]. The **Bg** is photo-written in a fibre with un-photo-written parts remaining besides with interfaces at any period position of the **Bg**. The multilayer is butted against one of those parts. The phase between the period of the **Bg** and this of the multilayer is any. The phase between the periods is then adjusted by several trials of polishing this fibre part and abutting it against the multilayer.



80 **Figure 1.c:** Schematic diagram of a **Bg-FP** as constructed in [13]. The phase shift introduced between the periods of the 2 parts of a **Bg** gives them the role of the 2 **Bg** mirrors of a **FP**.

85 Here, the **H-FP** simulations are taken over with a **3D** calculation method based on the expansion in eigenmodes and calculation of the propagation by **S-matrix**. This method used in [9, 10] is well adapted to the calculation of multilayer filters between fibres and has shown that diffraction is important through a very optically resonant **M-FP (Multilayer FP)** between optical fibres with narrow cores. To do this, we use a configuration of guided wave software distributed by Photon Design: Fimmwave for mode calculation, and Fimmprop for propagation calculation by **S-matrix**. Radially about the  $z$ -axis, the thin layers of the multilayer mirrors are each considered as a fictitious fibre with a uniform refractive index within the metal limit boundary conditions resulting in guidance. This

90 boundary is radially located at  $\rho = \rho_F$  far enough from the propagation axis for the electromagnetic field to be negligible ( $\rho$  is the radius in cylindrical coordinates around the  $z$  axis).

We are considering fibre optic technology here because it is well known by a broad community of researchers. But the concept of a hybrid **FP** with one mirror with a high refractive index step and the other with a low refractive index step can be extended to integrated optics technologies, which are  
95 very diverse. Of course, multilayer mirrors can only be realized at the external interfaces of integrated optics circuits, but it is possible to obtain mirrors with such a high index step as in multilayer mirrors even in the core of integrated optics circuits by using photolithography or etching. Moreover, the intermediate refractive index step range between that of thin films (from 0.1 to a few units) and that of photorefractive **Bg** (from  $10^{-6}$  to  $10^{-1}$  in silica [11]) is accessible in integrated optics by ion  
100 implantation [12]. Thus, in integrated optics, it is possible to produce hybrid filters whose mirrors have any index step between  $10^{-6}$  and a few units.

The first purpose is here to verify in which cases the assumptions made in [1] for the **1D** calculation are verified or not. Therefore, the properties of the **H-FPs** will be studied more fully than in [1] by **3D** modal simulation. In [4, 5], only experimental results on a fibred **H-FP** adjusted via the thickness of  
105 the interface layer of its multilayer with its **Bg** were presented: the theory and simulation will be extensively developed here. Weak spectral oscillation of the transmission in the rejection band, which had not been described nor interpreted before, are also studied here. We will show that the study of **IF-H-FP** contains information leading to a new quantitative model to interpret the **FP** properties of **H-FP** and **Bg-FP** without **IF**. Here, only single **H-FPs** are studied, and serial multiple **H-FPs** will be  
110 presented in another publication.

**Bg-FP** (figure 1 c) have been constructed by UV irradiation through a mask with a  $\pi$  phase difference between the periods of the 2 parts of the mask [13]. Provided that **Bg-FP** have poor rejection properties (as explained at the end of § 3.1), **FP** applications as bandpass filters are DWDM and sensors and are only industrially available in 2021 in non-fibre form thin film technology where the

115 bandwidth is at least 100 pm. We will see here quantitatively to what extent hybrid filters not only  
allow to strongly push back these limits, but also in fibre or integrated optics technology.

## 2. Theory

This chapter gathers and précises some more or less known elements useful to the readers as **S**-matrix  
formalism, the notation used for the multilayer and **Bg** inside the grating, the **S**-matrix simulation of  
120 **Bg**, and the concept of phase difference between the periods of 2 reflectors.

### 2.1. Summary reminder on propagation simulation by S matrix

Since the eigenmodes of the fibres are calculated in advance by Fimmwave, Fimmprop simulates  
propagation by a simple **S**-matrix calculation that is much faster than a direct analytical calculation  
would have been [8, 9, 10, 14]. In all the calculations made here, we study the system's response to  
125 mode 1 injected only as an input into the left access, the left access fibre being identical to the right  
access fibre having the same number  $d$  of modes. If power 1 has been injected in mode 1 on the left,  
the device response is given by the power coefficients  $T_{1n}$  and  $R_{1n}$  only, where the matrices **R** and **T**  
are sub-matrix of the **S**-matrix (modal Reflexion from left to left, and transmission from left to right).  
These coefficients check:

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$$1 = \sum_{n=1}^d T_{1n} + \sum_{n=1}^d R_{1n} + A + L_C \quad (\text{Eq. 1})$$

$A$  represents the absorption losses if not negligible.  $L_C$  is calculated by Fimmprop and represents the  
losses due to the calculation that exist if the number of modes or spatial resolution are insufficient. If  $A$   
 $= L_C = 0$ , and if there is no diffraction, for an **H-FP** between fibres in which the only mode 1 is  
injected on the left, Eq. 1 is reduced to  $T_{11} + R_{11} = 1$ . For such a filter, the other coefficients  $T_{1n}$  and  $R_{1n}$   
135 are all the more important as there is diffraction in the multilayer where the beam expanding from the  
fibres is not guided [9, 10].



## 2.2. Bg profiles notations & Bg S-matrix simulation

We call everywhere  $\lambda_0$  the centre wavelength for which the layers of multilayer mirrors are quarter-wavelength layers<sup>1</sup> and it is also chosen as the Bragg wavelength of the gratings. A multilayer mirror  
140 between identical **F** fibres is noted **F**,[(**HL**)<sup>*N*</sup>]**H**,**F** where **H** and **L** are High and low refractive index  $n_H$   
and  $n_L$  quarter-wavelength layers of thickness  $t_H$  and  $t_L$ , and  $N$  is the number of periods.

### Photo-refractivity radial profile of fibres and Bg

We consider here the case of the uniform photorefractive radial profile, which is the simplest to  
calculate. Let  $\Delta n(z)$  be the positive photorefractive variation along  $z$  of the refractive index. Let  $n_{co}$  and  
145  $n_{cl}$  be the original fibre indices considered uniform in the core and in the optical cladding, and the  
indices after UV irradiation  $n_{co,i} = n_{co} + \Delta n(z)$  and  $n_{cl,i} = n_{cl} + \Delta n(z)$  considered radially uniform. In the  
case where  $\Delta n(z) \ll n_{co} + n_{cl}$ , then the single mode approximation can be used, since the fundamental  
mode is almost the same in the photo-sensitized part as in the non-photo-sensitized part. Modal **3D**  
simulation will make it possible to verify in which cases  $\Delta n(z)$  is low enough for this approximation to  
150 be justified.

### Photo-refractivity axial profile of Bg's

The **Bg**'s obtained experimentally by interference [16] generally have a sinusoidal axial profile  
according to  $z$ , which is correctly sampled with 8 samples per period in the **1D** model [1]. It is also  
possible to realize step rectangular axial profile gratings by masking the photo-inscription UV beam,  
155 or by relative displacement of the fibre to be irradiated with an impulse UV laser.

**"Sinusoidal" Bg:** We choose to model the period of length  $\Lambda$  with a beginning and an end  
corresponding to a lack of photosensitization. Then, the core and optical cladding refractive index  
 $n_{co}(z)$  and  $n_{cl}(z)$  in the period are periods of sinusoids with minimums at the beginning and the end of  
the period and with a full amplitude  $\Delta n$ . We have checked that the effective index of the irradiated

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<sup>1</sup>  $\lambda_0 = 4nt$  for a layer of thickness  $t$  and refractive index  $n$

160 fibre follows also a sinusoidal law  $n_{\text{eff}}(z)$  with minimums at the beginning and end of the period and full amplitude  $\Delta n$ . The Bragg relationship for the fundamental mode is:

$$\int_{z=0}^{\Lambda} n_{\text{eff}}(z) dz = \frac{\lambda_0}{2} \quad (\text{Eq. 2})$$

The sinusoidal law  $n_{\text{eff}}(z)$  in Eq. 2 gives then:

$$\Lambda = \frac{\lambda_0}{2 \left( n_{\text{eff}} + \frac{\Delta n}{2} \right)} \quad (\text{Eq. 3})$$

165 Fimmwave has functions developed to edit such adiabatic evolution devices according to  $z$  (class of "tapers" where it is here the refractive index of the core and the optical cladding that vary slowly with  $z$ , and where an optimizing internal algorithm does not necessarily choose  $z_{s,j}$  samples of uniform length). This avoids editing each sample of a sinusoidal **Bg** as soon as you want to modify the precision of the sampling, which would be extremely tedious (would require editing each sample and  
 170 then calculating  $n_{\text{eff}}$  of its fundamental mode). Here, it is sufficient to enter the sinusoidal functions  $n_{\text{co}}(z)$  and  $n_{\text{cl}}(z)$  and specify "Min\_Step\_Frac"  $\triangleq MSF \triangleq \Delta z_{\text{Min}}/\Lambda$ , the parameter representing the minimum fraction of the sample in the period. Fimmprop obtains the exact period  $\Lambda$  of the **Bg** by scanning  $\Lambda$  to obtain a minimum of  $T_{11}$  of the **Bg** of the **H-FP** at  $\lambda = \lambda_0$ . We have carefully verified that the results are identical by introducing these elaborate functions or by introducing the period of  
 175 the **Bg** sample by sample. This verification was necessary because the exact way in which speed sampling is done by Fimmprop in the tapers is a trade secret that is not disclosed.

**“Quarter-wave” Bg:** We define this kind of step **Bg** as a grating with 2 samples per period, of different lengths, built quite like a quarter-wavelength multilayer mirror. The first sample of the **Bg** period is the input-output fibre of the **H-FP**. The other sample has its core and optical cladding indices  
 180 incremented by the same  $\Delta n$  value by photo-refractivity. The thickness of each sample is then:

$$t_{l,h} = \frac{\lambda_0}{4n_{eff,l,h}} \quad (\text{Eq. 4})$$

where the low and high effective indices of the fundamental modes of the respective 2 samples are involved. The quarter wave **Bg** is convenient to set the phase shift between mirror periods (e.g. by ending the **Bg** with a  $t_h$  photo-written **Bg** fibre section on which the first complete **H** layer of  $t_H$  thickness is deposited). So, the quarter-wavelength **Bg** leads to quick conclusions on step **Bg**'s with simulation, but is rarely manufactured, despite it could be with a mask.

Note that the difference in refractive indices between 2 samples adjacent inside a sinusoidal **Bg** becomes as small as desired by increasing the number of samples, allowing a very fast single mode calculation. Thus, in **3D**, the calculation of sinusoidal **Bg**'s in single mode approximation promises to be much faster than the mandatory multimode calculation of step **Bg**'s with high  $\Delta n$ . To predict the number of useful modes for simulating step **Bg**'s, we will proceed as follows:

- We consider only the fundamental mode in the input and output fibres, as well as in the non-photosensitized part of the **Bg** period, which is identical to these fibres
- By analysing with Fimmprop the device constituted by a single period of the **Bg**, composed of non-photosensitized fibre followed by a joint and with photosensitized fibre, we look for the expression of the mode of the 1st fibre of the period in the base of the modes of the second, i.e. the coefficients  $T_{1n}$  of the **S-matrix** of this device, retaining only the highest  $T_{1n}$  value modes. This composition of modes in the second fibre then reforms the fundamental mode of the first if it is injected into a subsequent period of the **Bg**, confirming the possibility of single mode simulation in the first fibre of the period. The acceptable limit is confirmed by checking whether for the global balanced hybrid filter,  $T_{11}$  is sufficiently close to 1 at  $\lambda_0$  with respect to the criterion that has been set.

Except for the determination of these limits, most of the properties of **H-FPs** are identical for sinusoidal or step **Bg**'s: we will therefore check them only on **H-FP** with sinusoidal **Bg**'s, faster to calculate.

### 2.3. Definition of the phase shift of the **Bg** and multilayer periods

The period phase definitions for initially setting intuitively the correct phase shift at the interface between the **Bg** period and that of the multilayer mirror are as follows:

- For the **Bg**, we set the phase origin at  $z_0 = 0$  where  $\Delta n_{\text{eff}}(z) = 0$ , and the phase of the period is defined as:

$$\varphi(z) - \varphi(z_0) = 2\pi \frac{\int_{z_0}^{z_0+z} \Delta n_{\text{eff}}(z) dz}{\int_{z_0}^{z_0+\Lambda} \Delta n_{\text{eff}}(z) dz} \equiv (2\pi) \quad (\text{Eq.5})$$

- Inside the quarter wavelength multilayer mirror, the beam is strongly multimode and bidirectional. The only simple approximation we can try to make before using Fimmprop is to assimilate it as in the **1D** model to a plane wave propagating orthogonally to a stack of layers of refractive indices  $n_L$  and  $n_H$ . The calculations made with Fimmprop will tell us if this approximation is justified. We set the origin  $z_0 = 0$  at the centre of a quarter wavelength layer **L**, and with the period thickness  $e_p = e_H + e_L$ , the phase of the period is defined as:

$$\varphi(z) - \varphi(z_0) = 2\pi \frac{\int_{z_0}^{z_0+z} n(z) dz}{\int_{z_0}^{z_0+e_p} n(z) dz} \equiv (2\pi) \quad (\text{Eq.6})$$

Thus, we can easily find that for a multilayer mirror, in the direction of increasing  $z$ , the phase is  $\pi/2$  at the beginning of an **H**-layer of the period starting in the middle of a layer **L**,  $\pi$  in its centre, and  $3\pi/2$  at its end.

For the **Bg**, we could find according to intuition that the phase is  $\pi$  in  $z = \Lambda/2$  and  $2\pi$  in  $\Lambda$ . On the other hand, only the integration formula makes it possible to find the less intuitive results<sup>2</sup>:

<sup>2</sup> Only if  $n(z)$  was constant over the period (which is not the case!) would we have found  $\varphi(z) - \varphi(z_0) = 2\pi$  mantissa of  $(z/\Lambda)$  and therefore the phase differences  $\pi/2$  instead of the 2 phase differences calculated just above.

$$\begin{cases} \varphi(\Lambda) - \varphi(3\Lambda/4) = \varphi(\Lambda/4) - \varphi(0) = \frac{\pi}{2} - 1 \\ \varphi(3\Lambda/4) - \varphi(\Lambda/2) = \varphi(\Lambda/2) - \varphi(\Lambda/4) = \frac{\pi}{2} + 1 \end{cases} \quad (\text{Eq.7})$$

225 Both Eq. (5, 6) will be used as first step to find the ideal phase jump between the periods of the **H-FP** reflectors in the **S**-matrix simulation.

### 3. Choice of H-FPs structures with perfect manufacturing

Concerning the manufacturing tolerances, the periodicity of **Bg** and multi-layer mirrors is sufficiently controlled [16, 17]. The delicate point is the control of the phase shift of their periods at the interfaces, particularly between the two different technologies of layer deposition and **Bg** cleavage or polishing. For a single serial **H-FP**, insufficient control of the thickness of the interface layer with the cleaved or polished **Bg** will result in a spectral shift of the transmission peak, and its subsidence.

The ideal bandpass filter has a narrow bandwidth with step flanks and a wide rejection band with a high rejection ratio. In this chapter, where we are just trying to choose the structures (multilayer formula and **Bg**  $z$ -profile), the manufacturing is assumed to be perfectly controlled.

Before introducing new material in this chapter, we recall some points introduced in [1]:

- The compactness of the **H-FP** according to  $z$  is mainly limited by that of the **Bg**.
- Outside the spectral areas where the gratings are reflective, an **H-FP** behaves like the multilayer it contains, i.e. a mirror whose reflection fixes the filter rejection.
- Multilayer mirror's reflection increases and approaches 100% when the number of layers is increased to a certain number determined by the qualities of the materials in terms of absorption.

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It is easy to check that the formula for multilayer is not suitable for **Bg** and vice versa (try for example the formula for **Bg** for multilayer with  $\Delta n_{\text{eff}} = 0$  in layer **L** and  $\Delta n_{\text{eff}} = n_{\text{H}} - n_{\text{L}}$  in layer **H**: the phase of the period is then constant all along the **L** layer, which is not convenient!).

- The rejection is wider band if the mirror is made with a pair of materials having a high step of refractive index between them, which also has the advantage of a faster deposition of fewer layers.

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- In any case, care should be taken that some moisture-sensitive materials must be encapsulated.

### 3.1. Obtaining balanced H-FPs

It had been demonstrated in [2] that when at centre wavelength  $\lambda_0$ , the **Bg** reflection equals that of the multilayer at  $\lambda_0$ , the **H-FP** is said to be balanced and a single bandwidth filter is obtained centred at the centre wavelength where the transmission is 100%<sup>3</sup>.

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To obtain a single 100% transmission bandwidth, for a given number of layers of the multilayer mirror, it is therefore necessary to adjust the number of periods of the **Bg** to obtain a balanced **H-FP**, which is observed when its transmission goes back to 100% at  $\lambda_0$ . This was done roughly in [1] by 1D simulation. Here, we make it accurately in **3D S-matrix** simulation. It is important not to make the mistake of optimizing the reflections of the multilayer mirror and Bragg grating separately at  $\lambda_0$  between 2 input-output fibres. Indeed, this gives a quite different result since the refractive index of one at less of the multilayer materials and that of the fibres are very different from each other. On the other hand, if the index step  $\Delta n$  of the quarter-wave **Bg** is fixed, it must be taken into account that the step of refractive index between the layers of the multilayer mirror being fixed at a different value, the values of the reflection coefficients are discrete and therefore cannot be adjusted perfectly. This is all

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<sup>3</sup> It had also been demonstrated in [2] that:

- When at centre wavelength  $\lambda_0$ , the reflection of the grating exceeds that of the multilayer, which is spectrally almost invariant, a double bandpass or bicorne filter is obtained, whose bands are centred on both sides from  $\lambda_0$  to wavelengths where the reflection of the grating equals that of the multilayer.
- When the **Bg** reflection is lower than that of the multilayer at  $\lambda_0$ , we obtain a single bandpass filter centred at  $\lambda_0$  but with a transmission level that is all the lower the more different these reflections are.

the more critical when  $\Delta n$  is high. So, unless  $\Delta n$  can be adjusted perfectly, the maximum transmission of the **H-FP** is in general slightly less than 1, even if the  $N_{\text{Per}}$  number of whole periods of the **Bg** is adjusted as best as possible.

### **H-FP vs Bg-FP comparison**

265 The main difference is that a **H-FP** has a spectrally uniform mirror over a very wide band compared to the main reflection band of its **Bg**. In a **Bg-FP**, **Bg**'s have identical secondary reflection peaks at the same wavelengths. So at all these wavelengths, the **Bg-FP** is balanced and has secondary transmission peaks up to  $T_{11} = 1$  in addition to the main transmission peak at  $\lambda_0$ . In addition to the narrow reflection band of their **Bg**, this is why **Bg-FPs** have a considerably narrower rejection band than **H-FPs**.

### 270 **3.2. Setting the phase shift of the multilayer and Bg periods**

Provided that the bundle of gratings has been photo-written and then cleaved or polished identically for every fibre by collective manipulations, adjusting this phase shift by adjusting the thickness of the interface layer of the multilayer as only experimentally done in [4, 5] has the advantage of easily allowing mass production by depositing at the end of a bundle composed of many fibres, but its accuracy is limited by that of the deposition technology used. On the other hand, the setting of the phase shift by UV photosensitization at the interface soon simulated in [1], subsequent to manufacturing, is not limited in accuracy, but is less easily suitable for mass processing. Here, we will therefore present the until now unpublished theory and simulations only of adjusting the thickness of the interface layer to evaluate its limits according to those of CVD technology.

280 Note  $\mathbf{F},[(\mathbf{HL})^N\mathbf{H},\pi,\mathbf{Bg}],\mathbf{F}$  or  $\mathbf{F},[\mathbf{Bg},\pi,(\mathbf{HL})^N\mathbf{H}],\mathbf{F}$  a simple **H-FP** between fibres **F**, and  $\mathbf{F},[\mathbf{Bg},\pi,\mathbf{Bg}],\mathbf{F}$  a **FP** purely in Bragg gratings noted **Bg-FP**. In each of these **FPs**, the mirror periods are out of phase by  $\pi$ .

- To obtain this phase shift in a **H-FP** with quarter-wave **Bg**, there are an infinite number of ways, but the easiest to program is to put a sample **h** of thickness  $t_h$  of the **Bg** (where **h** and  $t_h$

285 have been defined for the **Bg** in the same way as **H** and  $t_H$  for the multilayer) next to a layer **H** of thickness  $t_H$  of the multilayer mirror.

- In the case of **H-FP** with a sinusoidal **Bg**, regardless of the termination of the **Bg**, phase optimization can be simulated by scanning with Fimmprop the  $e_{trim}$  thickness of the **H** layer adjacent to the **Bg** to obtain a maximum of  $T_{11}(\lambda_0)$  for the **H-FP** (an experimenter would control the thickness of the adjacent **H** layer by measuring extremes of the transmission or reflection of the filter during its deposition).

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### 3.3. Shift of a plane wave FP transmission peak in function of $e_{trim}$ variations

$\lambda_v$  is the wavelength in the vacuum at the top of the transmission peak. We deduce after Eq. A8 that if the equivalent length  $L_{Eq}$  of the cavity (filled with uniform refractive index  $n_{eff}$ ) changes of  $\delta L_{Eq}$ , the wavelength of the considered Airy peak is translated in an inversely proportional way to  $L_{Eq}$  of the value:

295

$$\delta\lambda_v = \frac{\lambda_v}{L_{Eq}} \delta L_{Eq} \quad (\text{Eq. 8})$$

The Appendix A model on plane wave **FP** in which the reflection coefficients of the mirrors are real is useful especially for simulating **H-FP** with **IF** where the phase opposition between the periods of the mirrors is determined by adjusting the length of **IF**. For **H-FP** without **IF**, the multilayer mirror has a complex reflection coefficient whose complex exponential parts phase shift can be grouped into the phase  $\varphi$  defined in Eq. A2 and modified according to:

300

$$\varphi = 2 n_{eff} (2\pi f / c) L + 2 n_H (2\pi f / c) e'_{trim} \quad (\text{Eq. 9})$$

305 where  $e'_{trim}$  is a fictive suitable thickness of material **H** to express the phase shift between the mirrors, and remaining less than around  $\lambda_0$ . If the thickness  $e_{trim}$  of the layer **H** boundary with the **Bg** varies, we have  $\delta e'_{trim} = \delta e_{trim}$ . After Appendix A, we arrive to:



$$\Leftrightarrow \delta\lambda_V = \frac{n_H \lambda_V}{n_{\text{eff}} L_{\text{Eq}} + n_H e'_{\text{trim}}} \delta e_{\text{trim}} \simeq \frac{n_H \lambda_V}{n_{\text{eff}} L_{\text{Eq}}} \delta e_{\text{trim}} \quad (\text{Eq. 10})$$

310 The last approximation is valid because  $e_{\text{trim}} < \lambda_0$  and the results of § 4.6.3 will show that for any **H-FP**,  $L_{\text{eq}} \gg \lambda_0$ .

### 3.4. Secondary transmission peaks of the H-FP

The existence of a single peak transmitting almost 100% in a narrow band for the single **H-FP** is due to the uniqueness and spectral narrowness of the band where the **H-FP** is balanced. However, 315 secondary transmission peaks studied here for the first time may occur:

- Since at wavelengths other than  $\lambda_0$ , the multilayer keeps an approximately uniform reflection and much higher than that of the quasi-zero **Bg**, even for the much higher secondary reflection peaks of the **Bg**, the **H-FP** is very unbalanced. So, even with the right period phase shift, its corresponding secondary transmission peaks are therefore necessarily very low.
- 320 • Another source of low resonances outside the **Bg** reflection band could be the low dioptré between a feed fibre  $n_{\text{co,cl}}$  and the **Bg** fibre, which outside its reflection band is a fibre of average index  $n_{\text{co,cl}} + \Delta n/2$ .
- A conventional **FP** has spectrally uniform, infinitely thin mirrors, separated by a well-defined length  $L$ , and therefore 100% transmission Airy peaks separated by  $f = c / (2n_{\text{eff}} L)$ . This is not 325 the case here because the **Bg** has a few mm to a few cm lengths, and is spectrally selective.

Only numerical simulation will tell us whether such small secondary peaks have a significant amplitude anyway, and what are their spectral properties. For a first fast reading of the whole paper, we signal optional skip reading the chapters dealing with those simulations (4.5.1; 4.5.2; 4.6.2).

## 4. Simulation results

330 For the first time, **3D** simulations of hybrid filters are presented here. They will be used mainly to check the **1D** calculation on the main transmission peak of the hybrids, precise the interface layer thickness accuracy exigence, and also to simulate their unpublished secondary transmission peaks.

### 4.1. Simulation parameters and calculation convergence criteria

335 The calculations are all the more accurate when  $\rho_F$  is sufficient and the "precision parameters" are high, which are: the spatial resolution, the number  $N_{\text{Mod}}$  of modes in each fibre, and the minimal sample length in the **Bg** period. Nevertheless, quick and sufficiently accurate calculations are obtained for the lowest possible values of these parameters. The criteria used to ensure the accuracy of the calculations will not be recalled each time, but the methods generally used to set these parameters are among the following:

- 340 • Convergence of the system **S-matrix** according to the value of these parameters. Most often, only mode 1 (fundamental mode of the input fibre) is injected, and it is sufficient to check the convergence of  $T_{11}(\lambda_0)$
- Verification of the existence of  $L_C(z)$  losses due to calculations made by Fimmprop. The possible occurrence of calculation losses from a specific  $z$ -position in a device helps to find its  
345 origin.
- Convergence of the modal composition of the beam into one or more  $z$ -positions in the device
- These criteria must be applied to the complete device to be studied, but a preparatory work allowing a first evaluation of the precision parameters is for example to simply examine the injection of a mode of a fibre operating in the device into a neighbour fibre operating in the  
350 device.

Number of modes  $N_{\text{Mod}}$

The modes are such that their complex  $E_z$  component is  $E_z(\rho, \theta) = E_z(\rho) e^{im\theta}$ . Their real  $E_z$  component is then described by the  $m$  azimuthal and  $p$  polarization integer orders:

$$\begin{cases} \text{For modes with order } p = 1 \rightarrow E_z(\rho, \theta) = E_z(\rho) \sin(m\theta) \\ \text{For modes with order } p = 2 \rightarrow E_z(\rho, \theta) = E_z(\rho) \cos(m\theta) \end{cases} \quad (\text{Eq. 11})$$

355 If only a mode with  $m = m_0$  and  $p = p_0$  is injected into the input fibre, throughout the filter, it will then not be useful to consider modes other than  $m_0, p_0$  modes through all the device, which considerably speeds up the calculations (the integrals of overlap between modes of neighbouring fibres and of different orders  $m$  or  $p$  would be zero, as would the matrices  $\mathbf{S}$  of joint between these fibres).

In this publication, the power injected into the input fibre is always the fundamental mode (mode with  
360 highest  $n_{\text{eff}}$ ) in polarization  $p = 1$ , and with  $m = 1$ . Throughout the filter, it is therefore useless to consider in each fibre modes other than those with  $m = p = 1$ . The modes following the fundamental mode are numbered by decreasing  $n_{\text{eff}}$ , and have increasingly higher radial spatial frequencies. In each fibre, the accuracy of the beam expansion therefore increases with the number of modes. For a given radial resolution, the number of useful modes is therefore limited, because modes with a too high  
365 spatial frequency are calculated inaccurately. To check the validity of the modes of a fibre that must form an orthonormal base, Fimmwave tests their orthogonality. Number of useful modes:

- In access fibres: One mode is sufficient if only the transmission coefficients  $T_{11}$  and reflection coefficients  $R_{11}$  of the fundamental mode between the access fibres have to be calculated. This is always the case at  $\lambda_0$  for balanced **H-FP** that do not have diffraction to be evaluated and  
370 into which only the fundamental mode of the input fibre is injected.
- In multilayers: the modes in the uniform fictitious fibres simulating their layers are very different from the fundamental mode of the access fibres: therefore, a very multimodal calculation is here mandatory.
- In the Bg: The single mode approximation is all the better as:

- 375
- the photorefractive step modulation of the refractive index remains low in front of the refractive index of the core of the fibre in which the **Bg** has been photo-written (chosen here identical to the access fibres)
  - the variation according to  $z$  of the photo-refractivity is adiabatic (e. g. sinusoidal profile more adiabatic than step profile).

380 We consider the wavelength  $\lambda_0 = 1.55 \mu\text{m}$  throughout the simulations. For greater numerical clarity in the spectra, the wavelength is noted  $\lambda = \lambda_0 + \delta\lambda$ , and the spectra are all displayed according to  $\delta\lambda$ . The input and output fibres of all filters are of the SMF28 single mode standard for telecommunications at  $1.55 \mu\text{m}$  (step radial profile fibre with core radius  $4.1\mu\text{m}$ ,  $n_{\text{co}} = 1.449$ ,  $n_{\text{cl}} = 1.444$ ; simulated optical cladding extending only to  $\rho_{\text{F}}$  where the field is almost null). Multilayer mirrors are always chosen

385 here made with high index **H** in Si and low index **L** in  $\text{SiO}_2$  layers of quarter wavelength thickness at  $\lambda_0$ , and refractive indices of 3.48 and 1.444 respectively. These mirrors, whose layers have a high contrast index ( $\simeq 2$ ), when between two SMF28 fibres, have with only 7 layers ( $N = 3$ ) a reflection  $R_{11} = 99.65\%$  between fibres. We will keep  $N = 3$  everywhere, which allows us to obtain very resonant **H-FPs**.

## 390 4.2. Verification of the assumptions of the 1D calculation

The precision parameters that allow to converge better than 0.5% on the value of  $T_{11}(\lambda_0)$  are in all cases:

- $\rho_{\text{F}} \geq 20 \mu\text{m}$ . The results will show that the structures studied have almost no diffraction: also the beam extends little radially, and it is logical to be able to use  $\rho_{\text{F}}$  clearly weaker than in [9, 10] where the highly resonant multilayer **M-FPs** between SMF28 fibres studied introduce a lot of diffraction and where  $\rho_{\text{F}}$  had to be fixed at  $40 \mu\text{m}$ .
  - 49 modes in the layers of multi-layer mirrors
- 395

- A radial resolution  $N_{\text{Res}} = 1000$  for Fimmwave's cylindrical finite difference mode solver (FDM) used with electric wall boundary conditions (perfect metal).

- A  $\lambda_0/10$  spatial resolution of the modes.

For each  $z_{s,i}$  sample of the sinusoidal **Bg**, the calculation by Fimmwave shows that  $n_{\text{eff}}(z)$  strictly follows a sinusoidal law, as was only supposed in [1]. With a photorefractive amplitude  $\Delta n = 2 \cdot 10^{-3}$  and for  $N = 3$ , the **H-FP** with rectangular **Bg** is balanced with 2544 periods of the **Bg**, while the **H-FP** with sinusoidal **Bg** is balanced with 2679 periods of the **Bg** each with length  $A = 0.5355622 \mu\text{m}$  calculated with  $MSF = 0.025$ . The spectra  $T_{11}(\delta\lambda)$  of both **H-FPs** are represented in figure 2 in the 2 cases where their **Bg** are considered multimode (9 modes) or singlemode (1 mode). The following deductions are made:

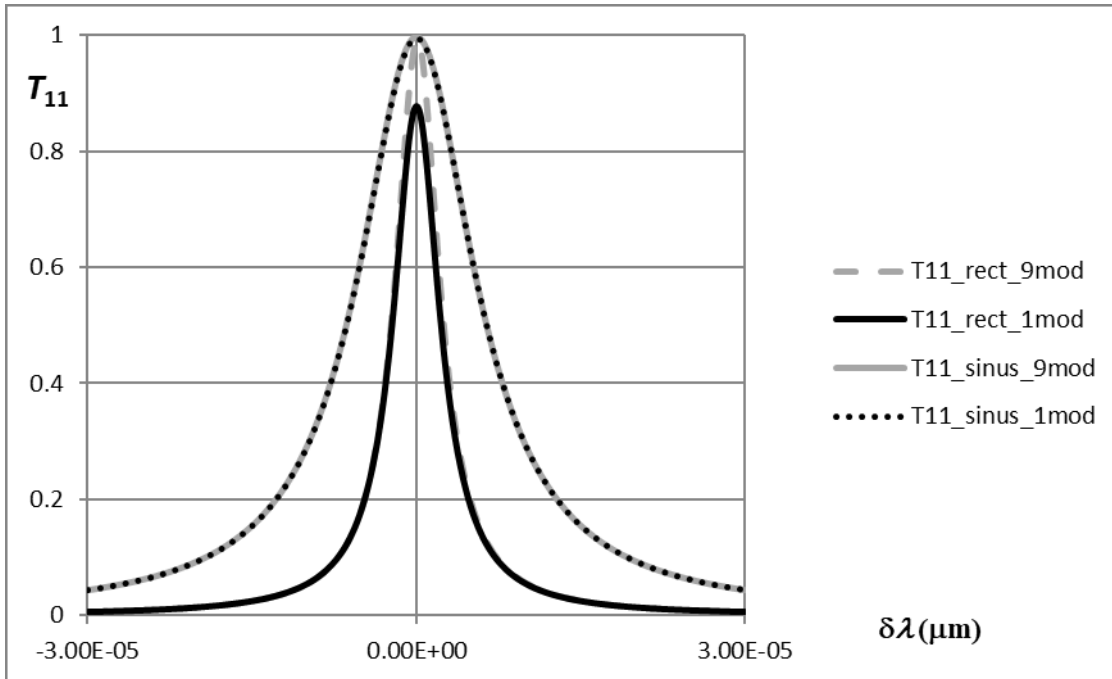
For the **H-FP** with quarter-wave **Bg**, the single-mode approximation in the **Bg** is not justified near resonance. In particular, the single mode 1D calculation made in [1] is only a rough approximation to the nearest 15% (estimated in figure 2 from the deviation of  $T_{11}(\delta\lambda)$  calculated with 1 or 9 modes<sup>4</sup>). It has been verified that the convergence of calculations allowing to have for the **H-FP**  $T_{11} > 99\%$  requires 9 modes in the photosensitized fibre of the **Bg** period. In the expansion of the fundamental mode of the un-irradiated fibre based on the modes of the irradiated fibre, the 1st power coefficient is 0.999999992, the next 8 are in the range  $[2 \cdot 10^{-9}, 10^{-7}]$ , and the next smaller ones, are neglected.

Contrary to what their low value would suggest, the coefficients of the 8 modes following the fundamental are not negligible in the calculation for the **H-FP** of  $T_{11}$  at  $\delta\lambda = 0$ : on the one hand because the **Bg** presents a large number of periods, and more especially because it is one of the mirrors of a resonant **H-FP**. On the scale of figure 2, we see that 9 modes are sufficient because the maximum of  $T_{11}(\delta\lambda)$  goes up to 99.13%. On the other hand, since  $T_{11}(\delta\lambda)$  approaches 100% better than 1% (most part of which is due to the discrete nature of the **H-FP** balancing with the adjustment of the number of periods in the **Bg**), and since the shift of the maximum of  $T_{11}(\delta\lambda)$  from  $\delta\lambda = 0$  is only -1.25 fm, the diffraction (accurately explained in [9, 10]) is negligible. Figure 2 shows that whereas the

<sup>4</sup> Be careful that the uninformed user satisfied with a single mode calculation in the **Bg** could have confused this deviation with diffraction in the multilayer!

single mode simulation gives  $T_{11}(\delta\lambda = 0) = 87.68\%$ , a resonance value 11.4% lower than that obtained by the multimode simulation, the difference is only significant near the **H-FP** resonance wavelength, which is the most important place to characterize a bandpass filter. For calculations outside the resonance, the single mode simulation is still correct.

For the **H-FP** with sinusoidal grating and a period  $\Lambda$  simulated with  $MSF = 0.025$ , the single-mode approximation is perfectly justified in the **Bg**, since  $T_{11}(\delta\lambda)$  rises to 99.54% with 1 mode<sup>5</sup>, and since the maximum transmission is precisely for  $\delta\lambda = 0$ . The transmission peak, which has a FWHM 12.84 pm is nearly 3 times wider than that of the **H-FP** with quarter-wavelength **Bg** (Fig. 2). The simulations have been done after setting  $e_{trim}$  to the right value as explained in next chapter.



**Figure 2:**  $T_{11}(\delta\lambda)$  for single **H-FPs** with quarter-wave rectangular **Bg** profile, or sinusoidal **Bg**, with 1 or 9 modes taken into account in the **Bg**. The curve  $T_{11\_sinus\_9mod}$  is masked by the curve  $T_{11\_sinus\_1mod}$  on which it is perfectly superimposed. Spectral resolution 257 points.

Table 1 shows some properties of balanced **H-FP** with sinusoidal **Bg** as a function of  $N$ , which determines the multilayer and therefore also the reflection coefficient  $R_{Bg}(\lambda_0)$  of the **Bg** alone between

<sup>5</sup> the single mode calculation at  $\lambda_0$  gives  $R_{11} = 2.74 \cdot 10^{-8}$  and  $L_C = 4.59 \cdot 10^{-3}$ ; whereas the 9 mode calculation gives  $T_{11} = 99.66\%$ ,  $\Sigma\{T_{1n} \text{ other than } T_{11}\} = 4.23 \cdot 10^{-5}$ ;  $\Sigma\{R_{1n}\} = 3.19 \cdot 10^{-3}$ ;  $L_C = 6.82 \cdot 10^{-4}$

fibres. In Table 1, these properties are represented for only one value of the photo-refractivity amplitude  $\Delta n$  of the sinusoidal **Bg**, as simulations show that  $N_{\text{Per}}$  and  $\Delta\lambda$  (FWHM of the transmission peak) are respectively almost inversely proportional and proportional to  $\Delta n$ . According to Eq. 3 or to a Fimmprop scanner calculation described in 2.2, the **Bg** period decreases slightly with  $\Delta n$ . Both ways of calculation give almost the same results<sup>6</sup>, and the result of Fimmprop is kept for later calculations by Fimmprop.

**Table 1: For a balanced H-FP with a sinusoidal Bg and  $\Delta n = 2 \cdot 10^{-3}$ , as a function of N of the multilayer:  $R_{\text{Bg}}(\lambda_0)$  between fibres,  $N_{\text{Per}}$  and  $\Delta\lambda$**

$N$	1	2	3
$R_{\text{Bg}}(\lambda_0)$	0.668	0.933	0.988 <sup>7</sup>
$N_{\text{Per}}$	1059	1870	2679
$\Delta\lambda$ (pm)	550.3	76.76	12.86

445

Let **H-FP1** be the single balanced multilayer **H-FP** with  $N = 3$  in Si/SiO<sub>2</sub>, and **Bg** sinusoidal with  $\Delta n = 2 \cdot 10^{-3}$ . For the balanced filter **H-FP2** identical to **H-FP1** without  $\Delta n = 2 \cdot 10^{-6}$ , and optimized  $e_{\text{trim}}$ , the calculation still gives good results with  $T_{11,\text{max}} = 0.997$  and FWHM = 13.3 fm, (so about 12.86 fm, which would correspond to an exact proportionality to  $\Delta n$  in comparison with  $\Delta n = 2 \cdot 10^{-3}$ ). In the following, we will no longer consider hybrids of this **FP** fineness for  $\Delta n$  less than  $2 \cdot 10^{-6}$ , which almost corresponds to the experimental limit of realization of **Bg**, and already allows FWHM as narrow as about 15 fm.

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<sup>6</sup> for  $\Delta n = 2 \cdot 10^{-3}$ , respectively  $\mathcal{A} = 0.5355627 \mu\text{m}$  and  $\mathcal{A} = 0.5355622 \mu\text{m}$  with the precision necessary for a bandpass centring at  $\lambda_0$

<sup>7</sup> The reasons why this value is lightly different from the 0.9965 value of the multilayer reflection between fibres are explained in Chapter 3.1.

### 4.3. Adjusting the phase shift between the period of the sinusoidal **Bg** and that of the multilayer mirror

455 The **H-FP1** simulation by **S-matrix** shows that:

- The phase shift between multilayer and **Bg** has been obtained for the ideal thickness  $e_{\text{trim}} = 0.2507736\mu\text{m}$ . Let us check whether the order of magnitude found for  $e_{\text{trim}}$  corresponds to the simplified model in §2.3. **H-FP1** consists of a **Bg** composed of an integer number of periods as defined in Eq. 3, followed by a multilayer. The phase of the period of the **Bg** at the interface is therefore 0 according to Eq. 5. The phase of the period of the multilayer must therefore be  $\pi$  at the interface, i.e. the interface must be at the centre of a quarter-wave **H** layer according to Eq.6. Experimentally, it is easier to deposit a slightly thicker layer  $[(0.5 + 2q) e_{\text{H}}]$  where  $q \in \mathbb{N}$ , which gives very similar spectral characteristics of the multilayer mirror. Since for  $q = 1$  Fimmprop gives an optimal value  $e_{\text{trim}} \simeq 2.25 e_{\text{H}} \neq 2.5 e_{\text{H}}$ , this shows that the simplified model of §2.3 is not justified. It just helps to explain the concept of phase jump between periods of **Bg** and multilayer, and the bi-directional multi-mode calculation in the multilayer done by **S-matrix** is indispensable to obtain quantitatively accurate results for the value of  $e_{\text{trim}}$ . So not all the hypotheses of the **1D** calculation are verified: in particular, the multimode calculation of the unguided beam in the multilayer is indispensable to find the right  $e_{\text{trim}}$  value (the simulations of 4.2 for the **H-FPs** gave a good result in some cases with a single mode calculation in the **Bg**, only because we had soon injected the right  $e_{\text{trim}}$  value calculated by **S-matrix** into the calculation).  
460  
465  
470
- As experimentally, the deposition of quarter-wavelength layers' stacks is done by measuring extremes of the reflection or transmission of the filter during deposition, we also simulated the deposition of the boundary **H**-layer at the end of the **Bg**. So, we verified  
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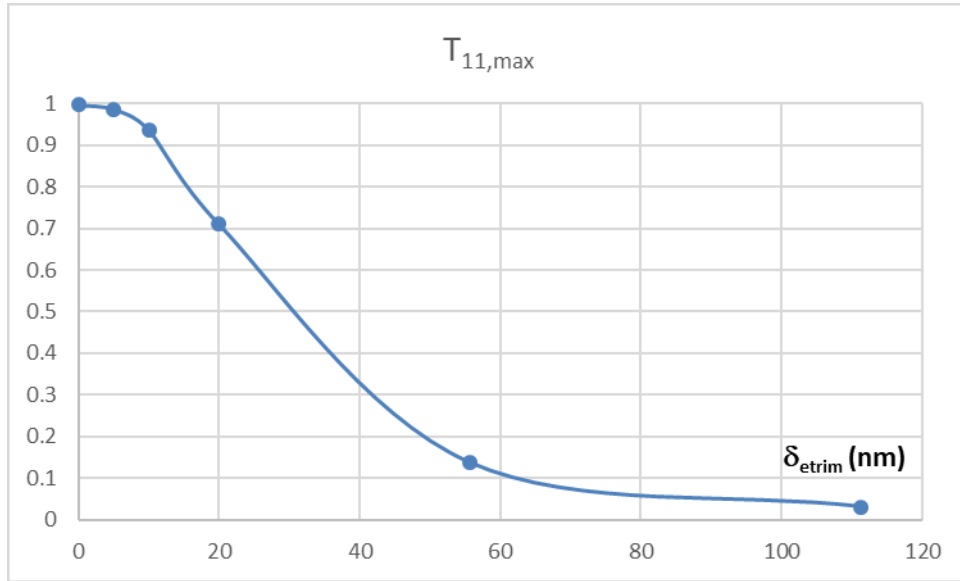
that the optimal  $e_{\text{trim}}$  value found for the overall filter gives a reflection minimum for the filter consisting only of the grating and an **H**-layer between fibres<sup>8</sup>.

- As shown in figure 3, an error  $\delta e_{\text{trim}}$  from 0 to about 5 nm on the thickness  $e_{\text{trim}}$  of the **H** layer adjacent to the **Bg** has almost no effect on the maximum value  $T_{11,\text{max}}$  of  $T_{11}(\delta\lambda)$  for **H-FP1**. It has been checked also:
  - That for  $\delta e_{\text{trim}} \leq 5\text{nm}$ , there is almost no broadening of the FWHM  $\Delta\lambda$  of the transmission peak.
  - That the curve  $T_{11,\text{max}}(\delta e_{\text{trim}})$  of figure 3 stays almost unchanged for any  $\Delta n$  decreasing until  $\Delta n = 2 \cdot 10^{-6}$  corresponding to **H-FP2**.
- The simulations show that the top of the transmission peak moves linearly in function of  $\delta e_{\text{trim}}$  as predicted by Eq. 10 with  $\delta \lambda_{\text{Max}} / \delta e_{\text{trim}} = +21.09 \text{ pm/nm}$  (this numerical value will be compared with these given by Eq. 10 only after knowing  $L_{\text{Eq}}$  established in § 4.6.3). By keeping  $N = 3$ , the simulations show that for  $R$  thus fixed,  $\delta \lambda_{\text{Max}} / \delta e_{\text{trim}}$  is also inversely proportional to  $\Delta n$ , which will be explained in 4.6.4. So, as  $\text{FWHM} \propto \Delta n$ , this shows that the ratio  $[\delta \lambda_{\text{Max}} / \delta e_{\text{trim}}] / \text{FWHM}$  is independent of  $\Delta n$ .
- The optical control of the deposit cannot be better than an atomic interlayer distance, i.e.  $d_C = (3^{1/2}/4) a = 0.235 \text{ nm}$  for the two closest planes of crystalline silicon with mesh parameter  $a = 0.543 \text{ nm}$  and a thickness of the same order for silica glass. The use of deposition to the atomic layer accuracy alone therefore leads at best to the accuracy of  $\delta \lambda_{\text{max}} / \text{FWHM} = 38.3\%$ .
- So, the experimenter will have to use all his know-how to adjust the optical thickness of the layers. For example, by using sophisticated optical control during the deposition, and technologies such as ion beam assistance [18], which makes it possible to slightly modify

<sup>8</sup> The minimum reflection thickness found for  $0.25070703 \mu\text{m}$  coincides to  $e_{\text{trim}}$  to the nearest relative  $3 \cdot 10^{-4}$

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the density of the material and thus globally the "mesh optical thickness". Other simple approaches that do not allow simultaneous filter production can be used to precisely compensate for the phase shift afterwards: sorting after series production, or additional UV photosensitisation near the interface area as simulated in [1], which can be made as precise as necessary by attenuating the UV beam.



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**Figure 3:** For **H-FP1**,  $T_{11,\text{max}}$  in function of  $\delta_{\text{etrim}}$ .

#### 4.4. Absorption losses

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**M-FP's** have an optically resonant layer between their 2 mirrors, which is responsible for absorption losses effects that can be important [9]. On the other hand, the phase opposition between the periods of the 2 mirrors of a **H-FP** does not require a resonant layer between them: since absorption exists only in the mirrors, low absorption losses effects are expected. We consider losses of 0.15 dB/km typical of telecommunication fibres. In Table 2, we consider typical losses of ordinary to optimal quality layers (from  $k = 10^{-4}$  to  $k = 10^{-6}$  where  $k$  is the imaginary part of their refractive index). It appears in table 2 that the effect of absorption is negligible with good quality layers, very low with the lowest quality layers, and a little bit worse for the narrower

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passbands<sup>9</sup>. Furthermore, we observed that the transmission peak in the presence of losses is neither shifted nor asymmetrical with respect to its peak apex. Losses by absorption will therefore no longer be considered here for **H-FP**'s. In comparison, in addition to diffraction losses, the absorption losses are the prohibitive element to realize **M-FP** with narrower bandwidth than 100 pm. For **M-FPs**, absorption losses do not only occur in the mirrors as for **H-FPs**, but especially in the layer between these mirrors, which is a multiple layer of **2H** or **2L**, and losses are therefore exacerbated in such an optically resonant layer.

**Table 2:** Losses effects

$k$	$T_{11,\max}(\mathbf{H-FP1})$	$T_{11,\max}(\mathbf{H-FP2})$
$10^{-4} *$	0.97117	0.92344
$10^{-5} *$	0.99284	0.98816
$10^{-6} *$	0.99504	0.99500
$0 *$	0.99529	0.99576
$0 **$	0.99543	0.99717

\* With 0.15 dB/km losses in fibres

\*\* Without losses in fibres

#### 4.5. Rejection and secondary transmission peaks

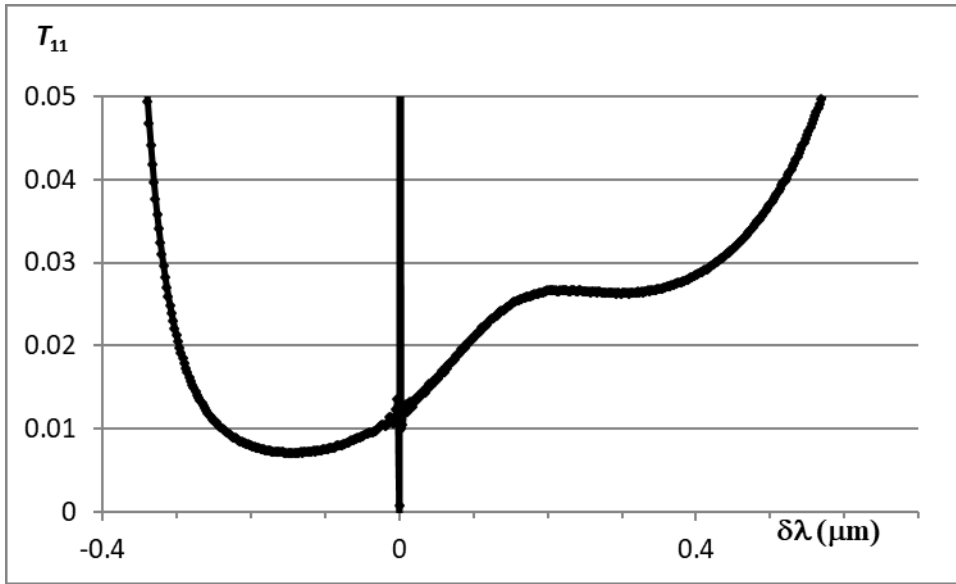
We have verified that the spectra of the simple **H-FPs** with rectangular quarter-wavelength profile **Bg** verify properties similar to those shown below for the **H-FP1** filter with sinusoidal **Bg** profile. As already noted in § 4.2, multimode simulation in the high index part of a rectangular profile **Bg** is essential mainly at the top of its main transmission peak. We have verified that apart from this peak, for the **H-FP** with rectangular quarter-wavelength profile **Bg** presented in § 4.2, a 9-mode calculation is much longer, but only makes a relative change of less than 4.5 per thousand (reaching the top of the largest secondary transmission peak). Therefore, for **H-FP** to **Bg** with

<sup>9</sup> Without absorption losses in the multilayer, the transmission of both filters appears to be excellent. It is surprising at first sight that the results are there very slightly better for **H-FP2**. But in fact, we are entering an area where computational accuracy should be pushed to the maximum, and this is not significant (as the results are soon excellent for both filters, spending too much time on it is not worth it here).

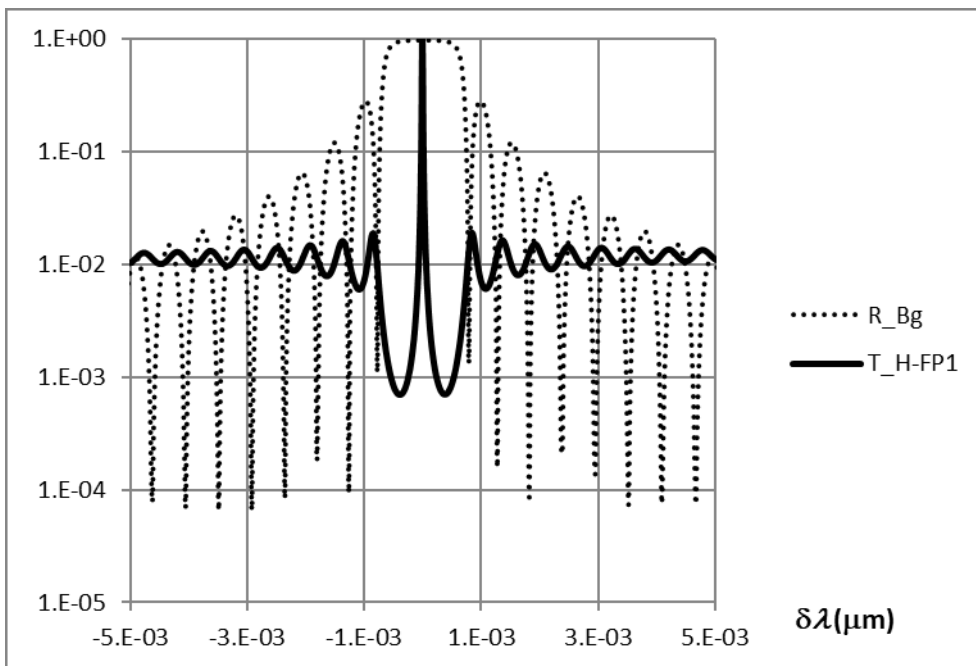
rectangular profile, the simulation can be single mode in the **Bg**, except for the main transmission peak.

535 So, the rejection is carefully studied below for the **H-FP1** filter. In figure 4.a, a very wide rejection band (width 0.7  $\mu\text{m}$  with  $T_{11} < 0.027$ ) appears around the transmission peak of **H-FP1**. This band is asymmetrical and has a much better rejection in some areas. In particular, a "super-rejection" band of 1.4445 nm width with  $T_{11} < 0.005$  appears (fig. 4.b). The super-rejection band corresponds substantially to the main reflection band of the **Bg** of **H-FP1** that we call **R\_Bg Band** (fig. 4.b). In this band, the reflections of the 2 mirrors of the **H-FP** are substantially equal, uniform and close to  
540 1, and their individual transmissions are  $T_1 = T_2 \simeq 1.2 \cdot 10^{-2}$  near  $\delta\lambda = 0$  (corresponds substantially to the average  $T_{11}$  of **H-FP1** outside the **R\_Bg Band** on Figure 4.b, where we verified that except the small spectral oscillations of its  $T_{11}$  described later, the **H-FP** is strictly equivalent to the multilayer mirror alone). Therefore, according to Appendix A, the minimum transmission that this **FP** can achieve is  $T_{\min} = T_l^2/4 \simeq 1.44 \cdot 10^{-4}$ , which explains well the existence of this super-  
545 rejection band if the minimum of  $T_{11}$  is close enough of this value. Figure 4.b shows that the minimum  $7.1 \cdot 10^{-4}$  of  $T_{11}$  achieved for **H-FP1** is intermediate between  $T_l$  and  $T_{\min}$ . The fact that  $T_{\min}$  is not reached simply means that the FSR (Free Spectral Range) of **H-FP1** is too much wider than the **R\_Bg Band**, which will be demonstrated quantitatively in § 4.6.3 by finding this FSR.

Apart from the **R\_Bg Band**, we analyse the **H-FP1** transmission in reference to 2 other bands  
550 describing the reflection of the **Bg**: the one called **O\_Bg Band** where the **Bg** reflection oscillates with still significant reflection values as in Figure 4.b, and this located outside the **O\_Bg Band** where the reflection of the **Passing Bg** is almost zero and flat, called **P\_Bg Band** (the **Bg** reflection peaks have there  $R_{11} < 1.1 \cdot 10^{-4}$ ).



555 **Figure 4.a:**  $T_{11}(\delta\lambda)$  on the entire **H-FP1** rejection band (transmission peak zone zoomed in fig. 4.b). Spectral resolution 513 points.



**Figure 4.b:**  $T_{11}(\delta\lambda)$  for **H-FP1** and  $R_{Bg} = 1 - T_{11}(\delta\lambda)$  of the included **Bg**. For **H-FP1**, the main transmission peak reaches  $T_{11} = 0.9955 \simeq 100\%$ . The most intense secondary peaks are closest to  $\delta\lambda = 0$  and have an amplitude  $\pm 0.78\%$  of the average rejection  $T_{11} = 1.2 \cdot 10^{-2}$  around and near the super-

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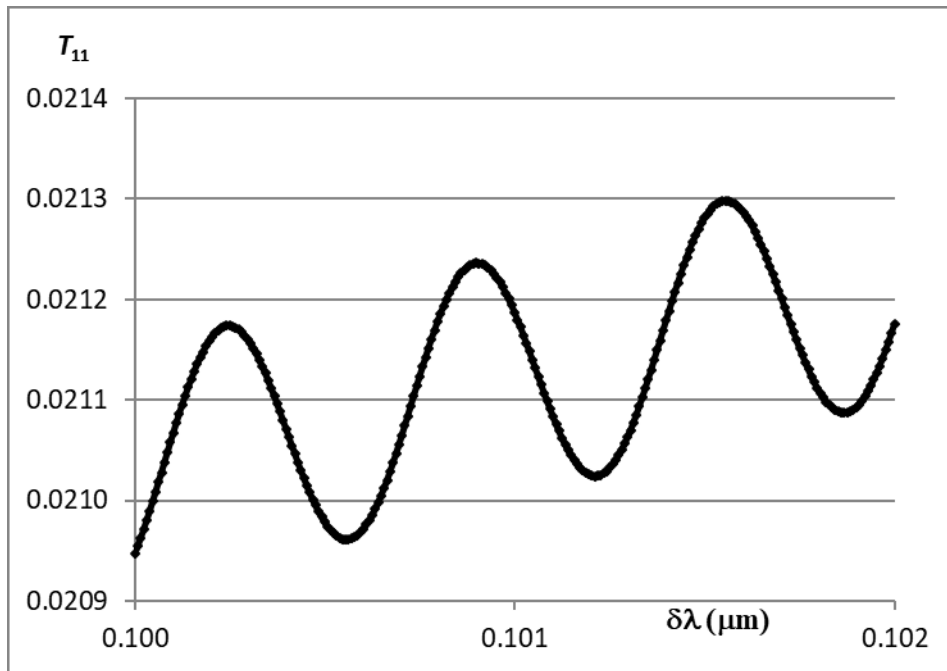
rejection band. The main reflection peak of the **Bg** corresponds well to the super-rejection of **H-FP1** and it is centred on the main transmission peak of **H-FP1**.

#### 4.5.1. Transmission of H-FP1 in the P\_Bg Band

The simulation in Figure 5 is small part of this band where the  $T_{11}(\delta\lambda)$  small peaks of **H-FP1** are closely spaced. It shows very evenly spaced **H-FP1** transmission peaks. We verified that the positions of these peaks do not correspond to the secondary reflection peaks of the **Bg**, which fall rather in anti-phase in the band of the figure, proving that there is no correlation. On the other hand, the positions of these secondary peaks correspond perfectly to a Fabry-Pérot effect between 2 mirrors spaced the length of the **Bg**<sup>10</sup>. We interpret it as one of the contingencies provided for in § 3.4 as the **FP** formed by:

- between the reflectors, the **Bg** considered in the **P\_Bg Band** as a homogeneous medium with an average refractive index  $n_{\text{eff}} + \Delta n/2$  where  $n_{\text{eff}}$  is the effective index of the fundamental mode of the non-photosensitized fibre.
- as reflectors, the multilayer mirror, and the dioptré of step of refractive index  $\Delta n/2$  between this homogeneous medium and that of the input or output fibre considered as another homogeneous medium of index  $n_{\text{eff}}$ .

<sup>10</sup> The peaks in figure 5 are at frequencies  $f_1 = 1.81665116 \cdot 10^{14}$  Hz;  $f_2 = 1.81593161 \cdot 10^{14}$ ;  $f_3 = 1.81521208 \cdot 10^{14}$  giving  $\text{FSR}_1 = f_1 - f_2 = 7.19551 \cdot 10^{10}$  Hz and  $\text{FSR}_2 = f_2 - f_3 = 7.19531 \cdot 10^{10}$  Hz. These FSRs have a relative variation of only  $2.78 \cdot 10^{-3}$ . The corresponding  $L_{\text{EQ}}$  length =  $c / (2 n_{\text{eff}} \text{FSR})$  is 1.439944 mm, identical to  $L_{\text{BG}} = 1.434771$  mm with  $\delta L/L = 0.33\%$  and  $f = c/(2nL) \implies \delta f/f = \delta L/L$ . It was calculated with  $n_{\text{eff}} = 1.446869$ , the average effective index of the fundamental mode in the **Bg** calculated according to Fimmwave, and for FSR the average of the 2 differences between the peaks above. For the calculation of the average  $n_{\text{eff}}$ , we start from  $n_{\text{eff}}$  calculated by Fimmwave for SMF28 at  $\delta\lambda = 0.101 \mu\text{m}$ , i.e. in the middle of the scanning range of figure 5, then add  $\Delta n$  photorefractive/2. For  $\Delta n = 2 \cdot 10^{-3}$  it comes average  $n_{\text{eff}} = 1.446869$ . Very similar results are obtained everywhere else in the **P\_Bg band**.



**Figure 5:**  $T_{11}(\delta\lambda)$  for the **H-FP1** filter showing some secondary transmission peaks of **H-FP1** in a rejection area of the **P\_Bg band** very far from the main transmission peak. The peaks oscillate +/- 0.01% around the average transmission of 2.1% (with an increasing slope as also visible in Figure 4a). Spectral resolution 257 points.

On the frequency point of view, the agreement is perfect to within 0.33% to consider that the oscillations of  $T_{11}$  for the **H-FP1** filter in the **P\_Bg band** correspond well to an equivalent **FP** of length  $L_{Bg}$  (see note 10 again). According to Eq. A5 and A6, the peak-to-peak amplitude of the oscillations should be  $T_1 \times 4 \times r_2$ . In Table 3, the amplitude of the oscillations have been corrected for the slope shown in Figure 5 at  $\delta\lambda \simeq 0.1 \mu\text{m}$ . Table 3 shows the interpretations of the amplitude of these oscillations according to 2 ways of calculating  $r_2$ . The calculation of  $r_2$  for a  $\Delta n/2$  step of refractive index dioptré gives worse results than the calculation of  $r_2$  made by Fimmprop, corresponding to the reflection of the entire **Bg** between an input fibre and the output fibre, for which the match is good for  $\delta\lambda$  corresponding to a flat average rejection (table 3 and fig 4.a). For  $\delta\lambda = 0.1 \mu\text{m}$ , corresponding to a significant slope of the rejection in fig 4.a, only the order of magnitude is quite good in table 3, and the inexact value comes presumably from the slope and the approximate origin of equations A5 & A6.

**Table 3:** Oscillations of  $T_{11}$  for **H-FP1** in three  $\delta\lambda$  places of the **P\_Bg band**

$\delta\lambda$ ( $\mu\text{m}$ )	$\simeq 0.1$	$\simeq 0.2$	$\simeq 0.3$
$T_1$	2.11E-02	2.66E-02	2.63E-02
Oscillations amplitude (Fimmprop)	2.12E-04	1.63E-04	1.21E-04
$T_1 \times 4r_2$ (a)	2.91E-05	3.67E-05	3.63E-05
$T_1 \times 4r_2$ (b)	5.22E-05	1.78E-04	3.83E-04

(a)  $r_2$  calculated for a  $\Delta n/2$  step of refractive index dioptré located at the fibre-to-**Bg**

(b)  $r_2$  calculated by Fimmprop for the reflection of the **Bg** between SMF28 fibres

#### 595 4.5.2. Transmission of H-FP1 in the O\_Bg Band

The situation in this band is well represented in figure 4.b, which represents the closest part of this band to the **R\_Bg Band**. Secondary transmission peaks spaced at the same order of magnitude as in **P\_Bg Band** are observed, but with some notable differences: these peaks are not regularly spaced in frequency (Table 4 corresponding to the peaks in figure 4.b), but closer to each other and more intense  
600 when they are closer to the **R\_Bg Band**. In figure 4.b, it is clear that these peaks do not correspond either with the secondary reflection peaks of the **Bg**. We suggest that the increase in the intensity of these peaks is however related to the increase in the intensity of the **Bg** 's secondary reflection peaks, and that their position results from simultaneity of:

- a **FP** effect identical to that described in the **P\_Bg Band**, predominant outside the secondary  
605 reflection peaks of the **Bg**
- another **FP** effect between the **Bg**, which has more and more effect in its secondary reflections, and the multilayer mirror.

**Table 4:** *FSR* between secondary peaks  $\delta\lambda < 0$  of fig. 4.b close to the main peak numbered 0

Pair of peaks ( $n^\circ$ )	0-1	1-2	2-3	3-4	4-5
<i>FSR</i> ( $10^{10}$ Hz)	10.47	6.57	6.93	7.04	7.04



## 4.6. Interleaved-Fibre-H-FP (IF-H-FP)

We consider here **H-FPs** similar to those made in [6], which include a length section  $L_i$  of non-photosensitized single-mode fibre interposed between the **Bg** and the multilayer mirror. Experimentally, this fibre section is one of the non-photosensitized ends of the fibre in which the **Bg** has been photo-written, cleaved or polished to adjust the  $L_i$  length, and abutment or glued with a multilayer mirror deposited on another single mode fibre to achieve an **H-FP**. The results of [6] show that  $L_i$  can easily be adjusted experimentally in a satisfactory way: for **IF-H-FP**, it is this adjustment that allows to obtain the desired phase shift between the multilayer and **Bg** periods by a more basic method for a non-multiple **H-FP**, than the adjustment of a layer of the multilayer mirror or a photorefractive correction, but less well adapted to the parallel manufacture of a large number of **H-FP**, or to the construction of a serial multiple **H-FP**. Here, we simulate **IF-H-FP** filters with sinusoidal **Bg**, whose simulation, lighter at all  $\lambda$ , is entirely singlemode in the **Bg**. In [6], a **1D** model was given, where the equivalent length of the **IF-H-FP** to a plane wave **FP** gives is  $L_{eq} = L_i$ . We will show here that this fits well for  $L_i \gg L_{Bg}$  by doing a **3D S-matrix** simulation of **IF-H-FP** in order to find the right model also for low values of  $L_i$ , and then also for  $L_i = 0$ .

### 4.6.1. Observation of the main peak centred at $\lambda_0$

The  $T_{11}(\delta\lambda)$  spectrum **3D** simulations of **IF-H-FP** with Fimmprop show the following behaviour:

- To maintain continuity when  $L_i \rightarrow 0$ , for the **H** layer at the interface with the **IF**, we keep in the simulations the  $e_{trim}$  value adjusted for **H-FP1** and therefore adapted for  $L_i = 0$ . For  $L_i \gg L_{Bg}$  (this restriction on  $L_i$  is evident according to Eq. 12 demonstrated later in 4.6.3),  $L_{Eq} \simeq L_i$  and the only values of  $L_i$ , which give  $T_{11}(\lambda_0) \simeq 1$ , are then such that for the fundamental mode of the interleaved fibre,  $L_i = M \lambda_0 / (2 n_{eff})$  with  $M$  integer (and where  $n_{eff} = 1.4460763$  is the effective index of the fundamental mode of the fibre at  $\lambda_0$ )<sup>11</sup>. The experimenter will prefer to

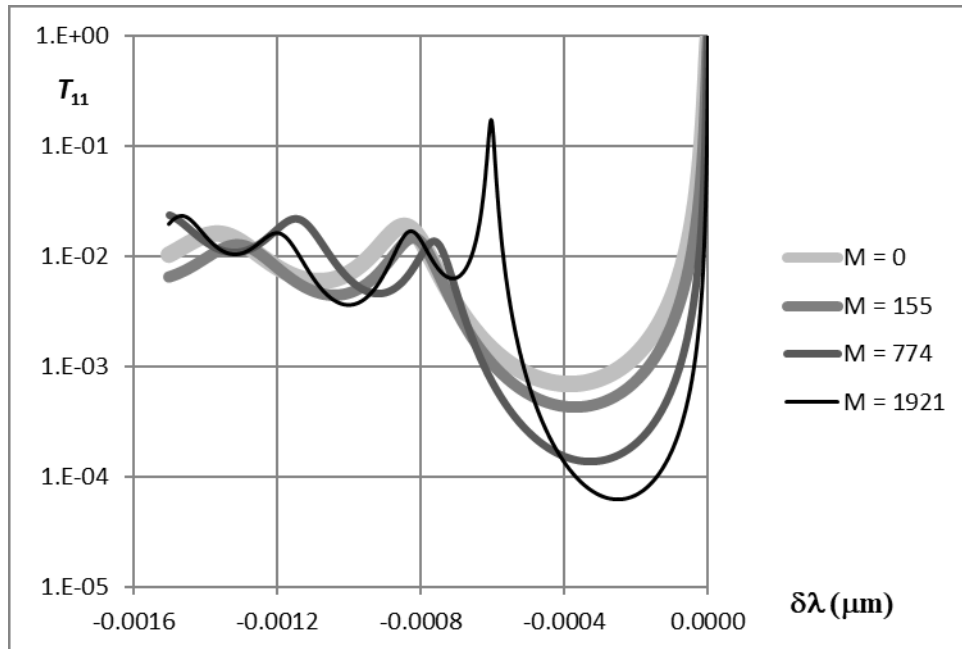
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<sup>11</sup> For example, for **IF-H-FP1**, a  $1921 \pm 0.3$  variation of  $M$  around its integer value  $1921 \iff L_i = 1028.9632\mu\text{m} \pm 0.161\mu\text{m}$  brings  $T_{11}(\lambda_0)$  below 40%. A polishing accuracy to within a few nanometres is therefore sufficient.

have the thickness  $e_H$  instead of  $e_{\text{trim}}$  for the **H** layer at the interface with the **IF** and will obtain the transmission peaks for (mantissa of  $M$ ) = 0.5 for  $L_i \gg L_{Bg}$ .

- The larger  $L_i$  and  $M$  are, the narrower the main peak is (fig. 6). **IF-H-FP** therefore have the advantage of an adjustable and narrower bandwidth, but do not have the robustness of a fixed technology and are sensitive to vibrations if the fibre is buffered and not glued to the multilayer (then well adapted to sensor applications). For the spectrum of **IF-H-FP1** following observations, the description is made with reference to the **R\_Bg Band**, **O\_Bg Band**, **P\_Bg Band** of the incorporated **Bg**.

635



640 **Figure 6:**  $T_{11}(\delta\lambda)$  for the **IF-H-FP1** filter with  $L_i$  corresponding to the values of  $M = \{0; 155; 774; 1921\}$ . They respectively result in an increasingly narrow transmission peak at  $\delta\lambda = 0$ , of which only the left part is represented here, the spectrum being almost symmetrical with respect to  $\delta\lambda = 0$  for the spectral band represented.

#### 4.6.2.Observations in the P\_Bg Band

645 Small secondary transmission peaks appear in figure 7, but not regularly, spectrally or in amplitude, unlike what was observed for **H-FPs** without **FI** in figure 5. Outside the **Bg** reflection band, we again

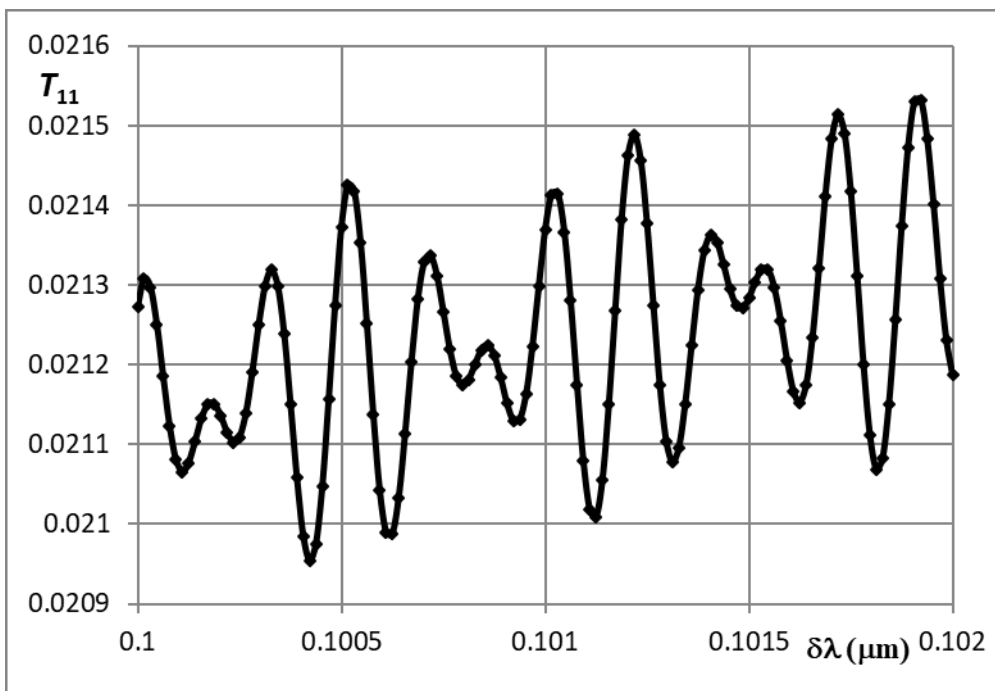
assimilate the **Bg** to a homogeneous medium with an average index  $n_{\text{eff}} + \Delta n/2$ . Three mirrors are involved, very thin ( $\mathbf{M}_1$ ), or of null thickness ( $\mathbf{M}_2, \mathbf{M}_3$ ):

- $\mathbf{M}_1$  = multilayer = mirror of almost zero thickness (thickness in the order of  $\lambda_0$ )
- $\mathbf{M}_2$  = dioptre **FI-Bg**, did not intervene in the **H-FP** without **FI**
- $\mathbf{M}_3$  = dioptre **Bg-input fibre**

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$\mathbf{M}_1$  alone has a high reflection coefficient, while  $\mathbf{M}_2$  and  $\mathbf{M}_3$  have the same tiny reflection coefficient as a  $\Delta n/2$  step of refractive index dioptre. The phenomena observed for the secondary peaks result from beats between the longitudinal modes of the 3 **FPs** formed by the 3 pairs of mirrors ( $\mathbf{M}_1$ - $\mathbf{M}_2$  separated from  $L_i$ ,  $\mathbf{M}_2$ - $\mathbf{M}_3$  separated from  $L_{\text{BG}}$ ,  $\mathbf{M}_3$ - $\mathbf{M}_1$  separated from  $L_i + L_{\text{BG}}$ ). Since the amplitude of these beats is low ( $<0.0005$  in figure 7 for **IF-H-FP1**), they have no disadvantage or interest for use as a bandpass filter, and their study will not be continued here.



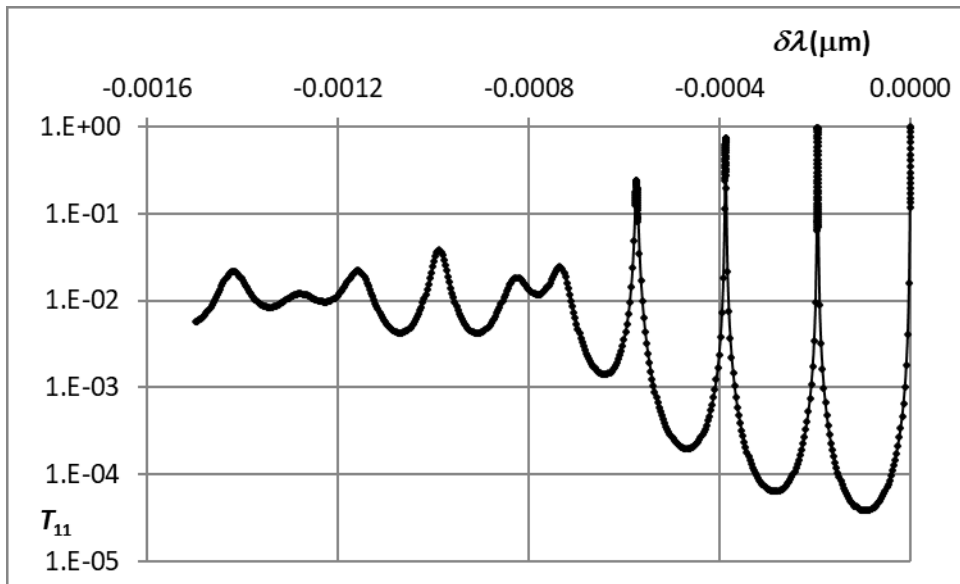
**Figure 7:**  $T_{11}(\delta\lambda)$  for the **IF-H-FP1** filter simulated with  $M = 7464 \rightarrow L_i \simeq 4.000$  mm, showing some

660

secondary transmission peaks in the same spectral band as in figure 5, very far from the **R\_Bg** band.

### 4.6.3. Observations in the R\_Bg Band and O\_Bg Band

In the **R\_Bg Band**, we consider only the reflections between the **Bg** and the Multilayer of reflection coefficients each close to 1 and preponderant, which form an effective cavity whose effects exceed those of all the other pairs of mirrors. These mirrors do not form a classic **FP**, since the **Bg** is a very thick mirror with very narrow reflecting band. The simulation shows that for **IF-H-FP1**, if  $L_i > L_{i,Th}$  ( $L_{i,Th} = L_i$  Threshold value), secondary peaks appear that are simultaneously in the **R\_Bg Band** and become larger than all secondary transmission peaks in the **O\_Bg Band** (fig. 6 & 8). For **IF-H-FP1**, we obtain  $L_{i,Th} = 723.51 \mu\text{m} \Leftrightarrow M_{Th} = 1350$ . The simulations show that this threshold is inversely proportional to  $\Delta n$ . This is because the spectral reflection width of a Bragg grating and therefore that of the super-rejection of an **H-FP** are also, as confirmed by simulations. Given the high value of  $L_{i,Th}$  in comparison with polishing accuracy, it is therefore easy to set  $L_i < L_{i,Th}$ .



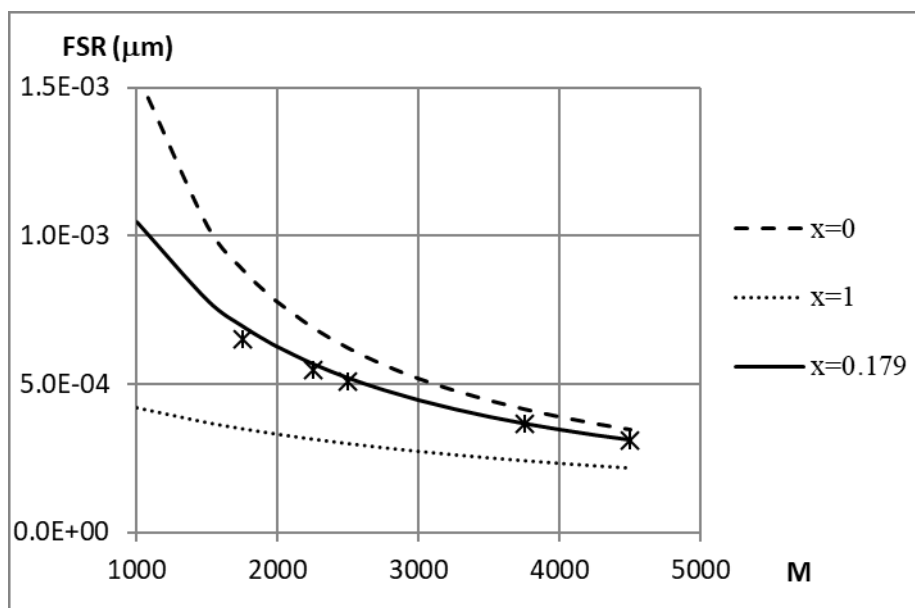
**Figure 8:**  $T_{11}(\delta\lambda)$  for **IF-H-FP1**- filter with  $M = 7464 \rightarrow L_i \simeq 4.000 \text{ mm} > L_{i,Th}$ , showing the left half of the main peak on the far right and some secondary transmission peaks. When located in the **H-FP1** super-rejection band, the first secondary transmission peaks are very narrow (this is why a few additional

calculation points have been added to the regular resolution of 513 points to precisely determine their vertex, which shows that the first one here goes back to 100%).

680 For  $L_i > L_{i,Th}$ , the simulation shows that for **IF-H-FP1**, secondary peaks appear close to the main transmission peak, exactly equidistant of the FSR of an equivalent conventional FP filled with a uniform medium having the refractive index  $n_{eff}$  of the fundamental mode of the fibre SMF28 at  $\lambda_0$ , and of equivalent length:

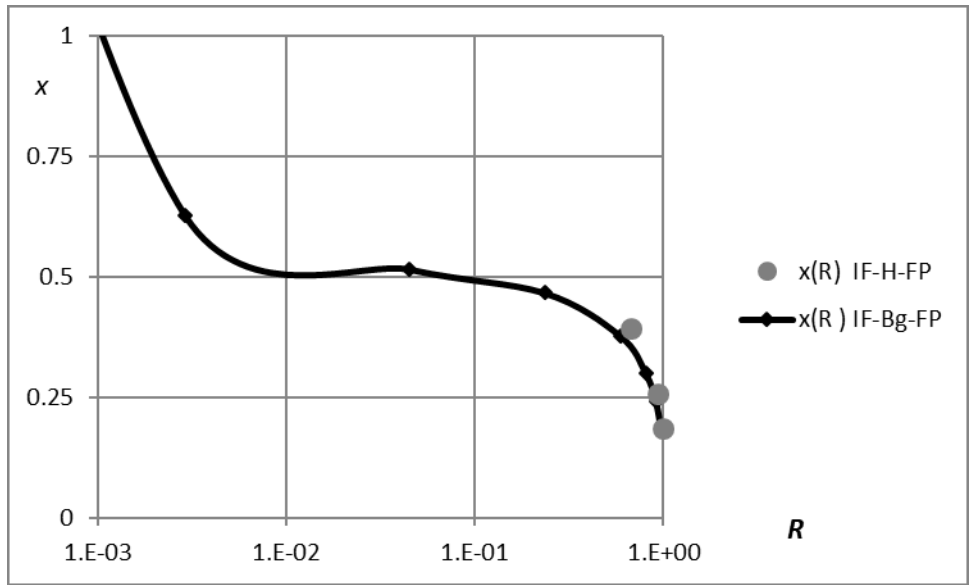
$$L_{Eq} = L_i + x(R)L_{Bg} \quad (\text{Eq. 12})$$

685 with  $x$  depending only on  $R$ , and  $x(R) = 0.179$  for the **IF-H-FP1** filter high  $L_i$  values (figure 9). So,  $L_{Eq}$  also represents the average length travelled by the fundamental mode passing through the real cavity. To determine  $x$ , only the largest values of  $L_i$  are considered, as those starting to approach  $L_{i,Th}$  only allow to observe a single secondary transmission peak whose position at the boundary between the **R\_Bg Band** and **O\_Bg Band** is disturbed (fig. 6, 8) by the other **FPS** described in § 4.6.2. Since the value of  $x$  appears constant in figure 10 for the large  $L_i$  values, we propose to keep the same value of  $x$  for all  $L_i$  values. Note that this new model, more precise than in [6] where  $x$  is zero, is consistent with the experimental observations described qualitatively in [6] for  $L_i \gg L_{BG}$ .



695 **Figure 9:** For **IF-H-FP1**, comparison of the FSR as a function of  $M$  simulated with Fimmprop between the main peak and the first neighbour (stars), with the FSR of a conventional **FP** of length  $L_{Eq} = L_i + x L_{Bg}$ , for various values of  $x$ . The value  $x = 0.179$  allows a good recovery for the large values of  $M$  corresponding to large  $L_i$ .

The simulation shows that  $x$  decreases sharply as the reflection coefficient  $R$  of the **H-FP** mirrors increases and approaches 1 (fig 10 where  $R$  of the multilayer and of the **Bg** depend on  $N$ , see table 1; the **IF-Bg-FP** also in figure 10 are discussed later in 4.6.4). We have verified that  $x$  does not depend on how  $R$  is obtained by choosing the photorefractive variation amplitude  $\Delta n$  of the **Bg**.



705 **Figure 10:** Dependence of  $x$  as a function of the reflection coefficient  $R$  of **Bg** for balanced **IF-H-FPs** (with  $N = 1, 2$  or  $3$ ), and balanced **IF-Bg-FPs** with various  $N_{per}$  each having  $M = 3464 \Leftrightarrow L_i \simeq 1.856$  mm, and sinusoidal **Bg** with  $\Delta n = 2 \cdot 10^{-3}$  similarly as for the **IF-H-FPs**. The **IF-H-FP1** filter corresponds to the right-most point of the figure with  $R = 0.988$ .

#### 4.6.4. Consequences of the equivalent FP model with $x$ independent of $L_i$

710 It should be emphasized that it was only the extension of Eq. 12 by keeping  $x$  invariable for low  $L_i$  values that allowed us to estimate the FSR of an **H-FP** without interleaved fibre. The logical

consequences of this model are not in contradiction with numerical simulations, which, without providing perfect quantitative evidence, confirm it as very likely:

- 715 • For **H-FP** without **IF**,  $L_{Eq} = x L_{Bg}$  is then the average length travelled by the fundamental mode passing through the real cavity, and is in good accordance found less than  $L_{Bg}$ .
- 720 • The FSR of a **H-FP** without **IF** is  $FSR = c / [2n_{eff} x L_{Bg}] = 3.182 \text{ nm}$  for **H-FP1**, i.e. significantly more than the 0.78 nm half-width of the corresponding **R\_Bg band**. Therefore, significant secondary peaks of **FP** resonance between the multilayer and the **Bg** cannot occur. Indeed, the observation of  $T_{11}(\delta\lambda)$  for **H-FP1** in Figure 4.b near of  $\delta\lambda = -FSR$  shows a weak transmission peak (the 5<sup>th</sup> secondary peak in the **O\_Bg band**). However, this belongs to a group of secondary peaks spaced far less than the FSR, and thus to a different phenomenon, which has already been described in § 4.6.2.
- 725 • For **IF-Bg-FP** with the same **Bg**'s as an **H-FP**, the validity of our model implies that we must obtain  $L_{Eq} = L_i + 2 x L_{Bg}$  with the same value of  $x$  as the **IF-H-FP** having even  $R$  mirrors and even  $L_i$ . This is precisely what is observed with the good overlap of the 2 curves in Figure 10. The **IF-H-FP** simulation only allows access to a small number of  $R$  values, given the high step of refractive index in its multilayer. On the other hand,  $\Delta n = 2 \cdot 10^{-3}$  being far much lower in the simulated **Bg** than in the multilayer, this allows access by varying  $N_{Per}$  to much lower, and much closer together,  $R$  values for **IF-Bg-FPs**. The case  $R < 10^{-2}$  is not considered, as it does 730 correspond to so weak reflectors, that it makes the usual **FP** calculation inappropriate. For the selected  $L_i$  value of fig. 10 and small values  $10^{-2} < R < 10^{-1}$ ,  $x(R)$  varies little around 0.5. For  $R > 10^{-1}$ ,  $x(R)$  then decreases sharply. Obviously, for **IF-Bg-FP**, in the case  $R = 1$ , the grating length is infinity, and this leads to  $x = 0$  (not represented on the figure because it corresponds to an infinity fineness inaccessible due to manufacturing tolerances and material absorption).
- 735 • For **Bg-FP** without **IF**,  $FSR = c / [2n_{eff} 2 x L_{BG}]$  is half that of the **H-FP** with the same **Bg** if we assume that each of the 2 **Bg** corresponds to an average path  $x L_{Bg}$  by the fundamental mode when crossing the cavity. Consequently, the widening of the main peak due to cavity

740 losses, which is  $FSR / F$  must be double for the **H-FP** than for the **Bg-FP** with the same **Bg** ( $F$  is the fineness [19] corresponding to both the **H-FP** and the **Bg-FP** with the same **Bg**). In addition, the width of the simulated peak, which may also have other origins, must be greater than the broadening by cavity losses. Our simulations confirm that the width of the main transmission peak of a balanced **H-FP** is indeed twice that of this peak for the **Bg-FP** with the same **Bg** as this **H-FP**. In addition, in figure 4.b., it appears that the FWHM of the line of the main transmission peak of **H-FP1** is 12.856pm. The calculation of the broadening due to the

745 losses of the equivalent cavity is indeed found to be lower and is 11.705 pm<sup>12</sup>. A plausible interpretation of the small difference is the consequence of the standard deviation of the length of the mean path of the fundamental mode in the cavity around its mean value  $x L_{Bg}$ .

- For **Bg-FPs** without **IF**, the simulations reported in 4.3 show that  $\delta\lambda_{Max} / \delta e_{trim}$  is inversely proportional to  $\Delta n$ . This corresponds perfectly to Eq. 10 & 12. Let us note however that if Eq. 10 allows to find the proportionality of  $\delta\lambda_{Max}$  to  $\delta e_{trim}$  and the order of magnitude of the proportionality coefficient, it does not allow to find its right value: indeed, in 4.3, Fimmprop gave for **H-FP1**  $\delta\lambda_{Max} / \delta e_{trim} = 21.09$  pm/nm, while Eq. 10 & 12 give  $\delta\lambda_{Max} / \delta e_{trim} = 14.53$  pm/nm. Again, this is because the assumption of a plane wave in the layers used to establish Eq. 10 instead of multimode propagation is inadequate.

#### 755 4.6.5. Manufacturing tolerances on $M$ and $L_i$ :

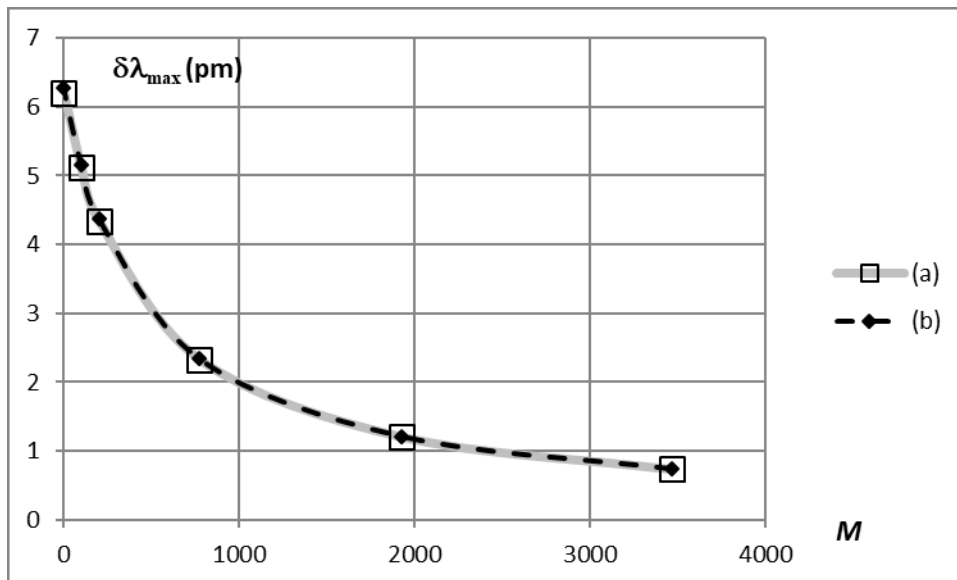
For **IF-H-FP1**, for an interleaved fibre SMF28,  $L_i = M \lambda_0 / (2 n_{eff})$  with  $\lambda_0 / (2 n_{eff}) = 0.535932993 \mu\text{m}$ <sup>13</sup>. When the integer part of  $M$  increases, the FWHM  $\Delta\lambda$  of the central transmission peak of the **IF-H-FP** decreases significantly as outlined in 4.6.1. The ratio between the shift of the transmission peak  $\delta\lambda_{Max}$  and  $\Delta\lambda$  depends only on  $M$ 's mantissa. For small variations of  $M$ 's mantissa around 0, the main peak degrades little. According to Eq. 8, this peak moves linearly as a function of  $\delta L_i$ . For **IF-H-FP1** and small variations of  $L_i$  from  $\delta L_i = 0$ , the Fimmprop simulation shows that the top of the main peak

<sup>12</sup> For H-FP1 filter,  $FSR = 3.046$  nm. The fineness  $F = \pi R^{0.5} / (1-R)$  with at  $\lambda_0$  the power reflection of the **Bg**  $\implies R = 0.9880 \implies F = 260.224 \implies FSR/F = 11.705$  pm.

<sup>13</sup> This accuracy corresponds to a mantissa accuracy of  $M$  corresponding to an uncertainty of  $\pm 1$  nm on  $L_i$  for  $M$  up to  $10^6$ , i.e.  $L_i \simeq 0.5$  m



shifts by  $\delta\lambda_{\text{Max}}/\delta L_i = +6.28\text{pm/nm}$ . For the adjustment of the **H** layer of **H-FP1** Fimmprop simulation in 3.3, we found  $\delta\lambda_{\text{Max}}/\delta e_{\text{trim}} = 21.09\text{pm/nm}$ , or 3.36 times more, which rendered the adjustment significantly more difficult in this case. This ratio should be compared with the ratio of the effective indices in the **H** layer (multimode certainly, but with effective indices each very close to 3.479 for the first dominant modes), and the effective index of the single-mode fibre  $n_{\text{eff}} \simeq 1.446$ , i.e. a different ratio of 2.41 with the same calculation accuracy. But it suggests that using a low refractive index like  $\text{SiO}_2$  at the interface renders the adaptation easier. Finally, it should not be forgotten that according to Eq. 8,  $\delta\lambda_{\text{Max}}/\delta L_i$  varies considerably according to  $L_i$  and so to  $M$ . This is observed in figure 11 where the calculation made from Eq. 8 & 12 also shows a perfect coincidence with the shifts of the main transmission peak of **IF-H-FP1** simulated by Fimmprop in function of the integer part of  $M$ . The calculation of figure 11 is made with  $x = 0.174$  (very close to the value  $x = 0.179$  retained above) and a mantissa of each  $M$  corresponding to  $\delta L_i = 1 \text{ nm}$ .



**Figure 11:** For  $\Delta L_i = + 1\text{nm} \Leftrightarrow \Delta M = + 0.00187$ , shift  $\delta\lambda_{\text{Max}}$  of the main peak of **IF-H-FP1** as a function of the integer part of  $M$ :

- a) Calculated with Eq. 8 & 12 for  $x = 0.174$
- b) According to the displacement with  $M$  of the peak top simulated by Fimmprop

## 5. Discussion

### 780 5.1. Modelling

The **3D S-matrix** simulations allowed us to check that only certain assumptions of the **1D** simulation model by **CMMS** presented in [1] are verified and only in some cases for **H-FP** without **IF**:

- Only a multimode calculation by **S-matrix** in the layers can find the correct values of  $e_{\text{trim}}$  and  $\delta\lambda_{\text{Max}}/\delta e_{\text{trim}}$  order of magnitude. We have shown that the experimenter can find himself  $e_{\text{trim}}$ ,  
785 which corresponds to a minimum of reflection of the filter during the deposition of the boundary layer with the interface. Nevertheless, the knowledge of this thickness by numerical simulation helps the experimenter to develop his process.
- A single-mode calculation in the **Bg** can only be performed for the **H-FP** with sinusoidal **Bg** even at optical resonance, and for **H-FP** with sharp step **Bg** outside resonance only.

790 For **BG-FPs**, there are no thin layers, and a single mode calculation in the fibre and in the **Bg** is possible, excepted at resonance in the case of sharp step **Bg**.

For **IF-H-FP**, the phase shift is set in the **IF**, which is single mode, so a single mode calculation can easily find the right fibre length to adjust the phase shift of the mirrors, and this length can easily be retouched afterwards, unlike the thickness of the adjusted interface layer of **H-FPs** without **IF**. So a  
795 single mode **1D** calculation is sufficient, except at resonance in the case of sharp step **Bg**.

Since the **CMSS** requires knowledge of the effective fibre indices, which are not calculated by common thin-film software, it is however preferable in all case to make all calculations with software such as Fimmwave/Fimmprop, which calculate fibre modes as well as **S-matrix** propagation, and have great programming flexibility to optimize sampling, thanks to their "adiabatic taper" algorithm.

800 To obtain balanced **H-FPs** whose transmission is 100% at the centre wavelength, the number of periods in the **Bg** must be carefully adjusted. For a given multilayer in the **H-FP**, this results in a smaller number of **Bg** periods and a narrower **H-FP** bandwidth in the case of a step longitudinal

profile **Bg** than a sinusoidal one. The discrete appearance of the **Bg** reflection coefficient according to its number of periods can prevent the transmission of the **H-FP** from increasing exactly to 100%, as  
805 more as the **Bg** index step is high.

The considerably wider rejection band for **H-FPs** than for **Bg-FP** reported in [1] has been studied here more fully. Around the transmission peak of the **H-FP**, there is a stronger rejection band whose spectral width corresponds to the reflection band of the **Bg**. Beyond that, the rejection, less strong, corresponds mainly to the reflection coefficient of the multilayer, however lightly degraded by very  
810 low secondary transmission peaks studied in detail here.

The study of strong **FP** oscillation (fig. 8) appearing in the reflecting band of **IF-H-FP** with  $L_{i,Th} \leq L_i \leq$  some  $L_{Bg}$  allowed to develop a new equivalent cavity model of length  $L_{EQ} = L_i + x L_{Bg}$  for the **IF-H-FP** and  $L_{EQ} = L_i + 2 x L_{Bg}$  for the **IF-Bg-FP**, where  $x$  depends only on the assumed reflection coefficient common to all mirrors (fig. 10). The trick to determine  $x$  for **H-FP** or **Bg-FP** without **FI** is to  
815 determine it for long lengths of interleaved fibre where  $x$  varies little (not too long either so as not to produce too sharp resonances that would disturb the calculations, and not too short so as those resonances do not vanish in the secondary transmission speaks studied earlier in the rejection band). Keeping this  $x$ -value for  $L_i = 0$ , where it cannot be determined otherwise, allows an excellent quantitative analysis of the line width of **H-FP** and **Bg-FP** taking into account their fineness, and to  
820 explain why the line width of the main transmission peak of a balanced **H-FP** is twice that of a **Bg-FP** whose **Bg** have the same reflection.

All these elements will help in the study of serial multiple **H-FPs** to be presented in detail in a later publication, which, like for bulk substrate **M-FPs**, simultaneously improve the rejection and spectral profile of the transmission peak of a single **H-FP**, but with more demanding manufacturing tolerances.

## 825 5.2. Performance and applications

The **3D** simulation of single **H-FP** shows that unlike **M-FPs** with the same Fineness between single-mode narrow core fibres, they exhibit no diffraction in the multilayer. In opposition, diffraction only allowed passbands of 2 to 3 nm for fibred **M-FPs**, and 0.1 nm for **M-FPs** on bulk, and for

sophisticated fibred **M-FPs** presented in [10]. But since the latter are difficult to achieve, non-multiple  
830 **H-FPs** are the simplest fully fibred filters to achieve for bandwidths from 15 fm, to 2 to 3 nm. This is  
very exciting, but the biggest difficulty with these filters is controlling the position of their pass  
wavelength  $\lambda_{\max}$  at which they have maximum transmission as a function of the phase adjustment of  
their mirror periods. We have shown that  $[\delta\lambda_{\max}/\delta e_{\text{trim}}]/\text{FWHM}$  is independent of  $\Delta n$ .

For an included **(HL)<sup>3</sup>H** Si/SiO<sub>2</sub> multilayer, the use of deposition to the atomic layer accuracy alone  
835 therefore leads at best to respective accuracies of  $\delta\lambda_{\max}/\text{FWHM} = 38.3\%$  for equilibrated **H-FP** filters  
and 11.49% for an equilibrated **IF-H-FP** near  $L_i = 0$ . This is insufficient for many applications, unless  
by chance the thickness grid accessible by atomic layer adjustment just happens to fall on the right  
value, or the filters are retouched one by one by photo-refractivity. Improving these results for mass  
production would require another publication focused on this subject, and of a mainly experimental  
840 nature, for which we suggest here only a few leads:

- A multilayer mirror terminated with a very high refractive index Si **H** matching layer gave us  
a very compact multilayer mirror and a fairly optimal multilayer reflection value. But the  
somewhat better result with polishing the interleaved silica fibre of lower refractive index  
suggests that the use of multi-layer mirrors terminated with SiO<sub>2</sub> or other low refractive index  
845 **L** material may allow somewhat better phase matching accuracy.
- In the same vein, it could be tried to dope the matching layer during its deposition, so that the  
available optical thickness grid is shifted when setting the thickness to the nearest atomic  
layer, so that the right value can be better achieved. Ion plating technology can work on this  
principle.
- In the case of mirrors produced by integrated optics photolithography, an experimental  
850 approach specific to each technology chosen is of course essential. It must also be considered  
that **Bg** with  $\Delta n = 2 \cdot 10^{-6}$  and the same reflection at  $\lambda_0$  than for **H-FP1** would be more than 1m  
long, which is not a problem for fibres, but for integrated optics it is, as it would require for  
example over 100 folding of the grating inside a 1 cm<sup>2</sup> square circuit.

855 For the same internal multilayer mirror and **Bg**, interleaved fibre filters have a narrower main bandwidth, and it is easy to obtain a bandpass filter with a single bandwidth since it is sufficient for the interleaved fibre length to be under just over 700  $\mu\text{m}$  for the **IF-H-FP** considered, and half for **IF-Bg-FP**.

From the point of view of their performance requirements, **FP** applications as bandpass filters with  
860 broad rejection band fall into two categories:

- The most demanding require control of the absolute bandwidth position
  - Signal applications: DWDM filtering for telecommunications (typical bandwidths 400, 200 or 100 pm until now [20]).
  - Spectrally absolute sensors: e.g. filtering of Raman Lidar Stokes and anti-stokes responses, filtering of fluorescence lines...
- Spectrally relative sensors for which only the displacement of the bandwidth following a variation of the mesurande is measured, only require that the bandwidth exists, but do not fix its position in an absolute way (e.g. pressure and/or distance sensor obtained by an air gap between the **FP** mirrors). On the other hand, these sensors require calibration.

870 Thus, it can be seen that fibre-optimised or integrated **H-FPs** with bandwidths as narrow as 15 fm and with a rejection of several hundred nanometres would greatly expand the possible applications.

For DWDM, it would become fully fibred on the one hand, and on the other hand, it would allow fine spectral processing within a metropolitan telecommunications network. Allowing spectral sorting with narrower bandwidths better suited to single subscriber selection as suggested in [21], this could  
875 increase the number of DWDM filters placed at the subscriber's premises and thus their market. However, for such applications leading to the manufacture of very large series of components, solving the phase matching tuning difficulty by front-end parallel processing is essential. On the other hand, relative sensor applications see their possibilities immediately increased considerably, as well as certain absolute sensors if they are manufactured in small numbers and if, in exchange for an increase  
880 in price, the individual adjustment of their phase matching, for example by photo-refraction, is acceptable with respect to their market (in this case, **IF-H-FP** can be more flexible to realise, but less stable over time).

## 6. Conclusion

885 Despite they are partially constructed with un-guiding layers, the modal **3D** simulation of hybrid **FP** shows no diffraction, and the absorption effects are also negligible, both in opposition to multilayer **FP** between narrow core fibres. Their **3D** simulation by **S**-matrix, which is highly multimodal in the layers, is essential in the case of **H-FPs** without interposed fibre to find the thickness of the layer at the interface with the grating. Once this has been found, and also for **H-FPs** with interleaved fibre or purely in **Bg**, their multimodal simulation in the grating is only indispensable at the top of their 890 transmission peak, only in the case where their grating has a sharp step axial refractive index profile. Their very broad and large rejection, far wider than that of **BG-FP**, is similar to that of their multilayer mirror (with weak oscillations studied precisely here), except in the main reflection band of their **Bg** where it is much stronger. The control of the layer thickness at the interface is not critical for the collapse of a peak broader than 15 fm, but is critical for controlling its shift. So, 15 fm passband filters 895 can be obtained for individual devices and also industrially for spectrally relative sensors. But applications with an absolutely fixed wavelength and requiring large industrial production such as DWDM require an experimental research effort in each chosen technology for a better control of the passband shift, and passband of 1.5 pm to 150 fm would be more realistic for integrated optics because of the grating length. Every small spectral oscillations appearing in the rejection band of the **H-FP** 900 have been accurately observed and interpreted. The simulation of hybrids with interleaved fibre between mirrors allows us to show for certain properties the equivalence of a hybrid without interleaved fibre with a **FP** travelled by plane waves and with localized mirrors, having for length a fraction that we have determined of the length of their **Bg**. The same is true for all properties of a **FP** with 2 **Bg** identical to that of the hybrid, where the equivalent cavity length is found to be double.

## 905 Appendix A: Formalism for plane waves FP interferometers

The intensity transmission of a **FP** is expressed as a function of its Airy transmission [20], which is:

$$T_A = \frac{1}{(1-m)^2 + 4m \sin^2(\varphi/2)} \quad (\text{Eq. A1})$$

As they will be proved to have negligible effect here, we will not consider losses by absorption, and the loss factor is therefore  $m = r_1 r_2$  where  $r_1, r_2$  are the amplitude reflection coefficients of the mirrors; we will also consider  $R_1, R_2$  the intensity reflection coefficients and  $t_1, t_2, T_1, T_2$  the amplitude and intensity transmission coefficients of these mirrors. The transmission in intensity of the **FP** is then  $T = T_1 T_A T_2$ . We will often consider for the cavity equivalent to a single mode propagation between 2 ultra-thin mirrors, the phase  $\varphi$  of a round trip in the cavity, which is:

$$\varphi = 2kL = 2 n_{\text{eff}} (2\pi f / c) L_{Eq} \quad (\text{Eq. A2})$$

where  $k$  is the wave vector in the cavity,  $f$  is the frequency and  $L_{Eq}$  is the equivalent length of the cavity filled with  $n_{\text{eff}}$ . For  $\varphi = 2p\pi$  and for  $\varphi = (2p+1)\pi$  where  $p$  is a natural integer, the maximum and minimum transmission values are obtained respectively:

$$T_{\text{max}} = \frac{1}{(1-m)^2} T_1 T_2 \quad (\text{Eq. A3}) \quad \text{and} \quad T_{\text{min}} = \frac{1}{(1+m)^2} T_1 T_2 \quad (\text{Eq. A4})$$

The extreme transmissions of the cavity  $T_{\text{max}}$  and  $T_{\text{min}}$  can be easily specified after limited development calculations in some particular cases that will facilitate our reasoning following the simulations, and for which mirrors transmissions  $T_1 T_2 = |t_1|^2 |t_2|^2$  if we consider identical media on each side of the FP:

- For 2 identical mirrors with reflection coefficients  $R_2 = R_1$  close to 1, since then the loss factor  $m \simeq R_1$  and  $T_1 = 1 - R_1$ , we find  $T_{\text{max}} = 1$  and  $T_{\text{min}} = T_1^2/4$ .
- For one mirror  $R_1 \simeq 1$  and the other mirror  $R_2 \simeq 0$ , since then  $m \simeq r_2$  reflection amplitude and  $T_2 \simeq 1$ , we find values close to  $T_1$ , which are:

$$T_{\text{max}} \simeq T_1 (1 + 2r_2) \quad (\text{Eq. A5}) \quad \text{and} \quad T_{\text{min}} \simeq T_1 (1 - 2r_2) \quad (\text{Eq. A6})$$

$T_A$  has a transmission peak each time  $\sin(\varphi/2) = 0$ , which is obtained at the frequencies

$$f = p \frac{c}{2n_{\text{eff}} L_{Eq}} \Leftrightarrow \lambda_v = \frac{c}{f} = \frac{2n_{\text{eff}} L_{Eq}}{p} \quad (\text{Eq. A7})$$

where  $p$  is the interference order, and  $\lambda_v$  is the wavelength in the vacuum of the top of the transmission  
 930 peak ( $p_0$  is the order for  $\lambda_v = \lambda_0$ ). We deduce that if the length of the cavity changes from  $L$  to  $L' = L + \delta L$ , the wavelength of the Airy peak of order  $p$  is translated proportionally to  $L$  of the value:

$$\delta\lambda_v = \frac{2n_{\text{eff}} \delta L_{Eq}}{p} = \lambda_v \frac{\delta L_{Eq}}{L_{Eq}} \quad (\text{Eq. A8})$$

A variation in the thickness of the **H**-layer next to the **Bg** introduces a phase term to the reflection  
 935 coefficient of the multilayer mirror, which can no longer be considered real. Here we make the approximation that the beam is a plane wave in the H-layer. This phase shift can then be represented by a thickness  $e'_{\text{trim}}$  of material **H**. Thus, Eq. A2 becomes:

$$\varphi = 2 n_{\text{eff}} (2\pi f / c) L + 2 n_H (2\pi f / c) e'_{\text{trim}} \quad (\text{Eq. A9})$$

This thickness can always be written as  $e'_{\text{trim}} = e_0 + e_{\text{trim}}$ , where  $e_0$  is a constant thickness whose value does not matter: so,  $\delta e'_{\text{trim}} = \delta e_{\text{trim}}$ . The Airy peaks correspond to  $\lambda_v$  such that  $\sin(\varphi) = 0$ , i.e.:

$$940 \quad \lambda_v = \frac{2n_{\text{eff}} L_{Eq} + 2n_H e'_{\text{trim}}}{p} \Rightarrow \frac{1}{p} = \frac{\lambda_v}{2n_{\text{eff}} L_{Eq} + 2n_H e'_{\text{trim}}} \quad (\text{Eq. A10})$$

For a fixed  $p$ -order peak, it comes:

$$\delta\lambda_v = \frac{2n_H \delta e'_{\text{trim}}}{p} = \frac{2n_H \delta e_{\text{trim}} \lambda_v}{2n_{\text{eff}} L_{Eq} + 2n_H e'_{\text{trim}}} \approx \frac{n_H \lambda_v}{n_{\text{eff}} L_{Eq}} \delta e_{\text{trim}} \quad (\text{Eq. A11})$$



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