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Widely Tunable Directional Coupler Filters with 1D Photonic Crystal

Bożena Jaskorzynska (1)*, Zygmunt Jacek Zawistowski (2), Matteo Dainese (1)
Julien Cardin (1), Lars Thylén(1)

(1)* Royal Institute of Technology (KTH), Department of Microelectronics and Information Technology, Kista
Photonics Research Center (KPRC), Electrum 229, SE - 164 40 Kista, Sweden

Tel: +46 8 790 40 62, Fax: +46 8 790 40 90, e-mail: bj@imit.kth.se

(2) Institute of Fundamental Technological Research, Polish Academy of Sciences, Department of Theory
of Continuous Media, Swietokrzyska 21, 00-049 Warszawa, Poland, e-mail: zzawist@ippt.gov.pl

ABSTRACT

We present two concept examples for adding a wide range tunability to Si/SiO₂ devices involving a photonic crystal element. They are based on a directional coupler filter of two different geometries, where one of the arms is a Bragg Reflection Waveguide (BRW) used for the bandwidth improvement. The tuning relies on changing the properties of the BRW core. As an illustration we consider the smectic A* liquid crystal as the core material and show that ca 100 nm tuning range is achievable by the core index variations of 0.006 under applying electric field of 5 V/μm.

Keywords: optical filters, directional couplers, Bragg reflection waveguides, photonic crystal, liquid crystals, electrical tuning.

1. INTRODUCTION

Devices employing photonic crystals (PhC's) provide unique dispersion properties that can be utilized for realizing delay lines, dispersion compensators, enhanced efficiency wavelength converters and amplifiers, or narrow bandwidth filters and lasers. Most of the reported so far PhC based components, however, are not tunable, especially those made in silicon. Adding a tuning mechanism is desired for dynamically reconfigurable WDM networks, where the wavelength allocation is changed as the needs of the network change. It is of particular interest to add a wide range dynamic tuning to PhC devices in the low-cost, but passive Si/SiO₂ technology compatible with optoelectronics and the transmission fibres. This can e. g. be achieved by including micro-electro-mechanical systems (MEMS) elements, or by incorporating electro-optic materials, such as polymers or liquid crystals (LC's). Here, as an example of a device providing a wide continuous tuning and benefiting from the dispersion properties of a PhC element for the bandwidth narrowing, we consider an extension of our earlier proposed and demonstrated [1, 2] directional coupler filter where one arm is a Bragg Reflection Waveguide (BRW), i.e. a 1D PhC waveguide. The extended concept relies in essence, on making the BRW core tunable. In the presented example we simulated tunability of the core refractive index, for which we choose the smectic A* LC's, having the response time in the sub-microsecond regime [3], i.e. three orders of magnitude shorter than that of nematic LC's or of the thermo-optic phase shifters. However, the concept and the conclusions are also applicable to the case when the core width is tuned, with e. g. MEMS.

We consider and compare two geometries. One being a direct extension of [2] and presented in [4], where the silicon core is replaced by LC, and a new design where one of the BRW claddings is removed and the LC forms an overlay of the coupler. The latter is much easier for practical implementation and still, as we show, preserves similar performance when properly designed.

2. FILTER GEOMETRIES AND PRINCIPAL OF OPERATION

The filters we consider are both directional couplers with dissimilar arms [5]. Their cross sections are depicted in Fig. 1. One of the arms is a conventional (index guided) channel waveguide with a GeSiO₂ ($n_2 = 1.465$) core buried in a silica glass ($n_1 = 1.4558$). It is single mode in a wide wavelength range around 1.55 μm. The other arm is a LC core with two (Fig. 1a), or one (Fig. 1b) Bragg Reflector claddings consisting of alternating layers of amorphous silicon ($n_2 = 3.55$) and silica. The layer thicknesses, different for each of the cases, are given in Fig. 1. Only transverse electric (TE) waves are considered for which the extraordinary refractive index of the LC core (smectic A* BDH764E with a 45 deg pretilt in the plane parallel to the Bragg layers – see [4]), is tuned from its off-state value $n = 1.5657$ by ± 0.006 , which is only a half of the refractive index change possible for this liquid crystal. This corresponds to ± 5 V/μm variations of the electric field applied between ITO electrodes placed at both sides of the LC core. The LC core can be regarded as a defect in 1D PhC formed by the Bragg layers. The whole, vertically etched structure is buried in a silica glass cladding, however in the case (1b) there is no glass on the top.

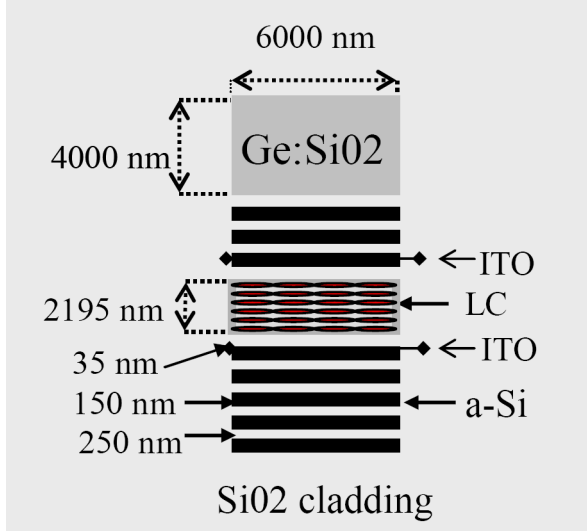


Figure 1a. Cross-section of the directional coupler filter with the "full BRW" arm.

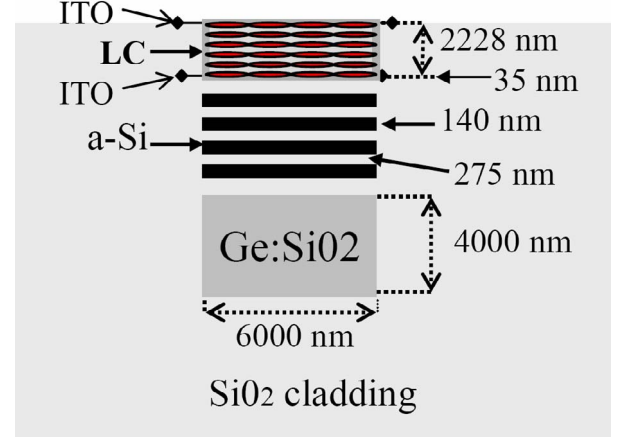


Figure 1b. Cross-section of the filter with the "LC overlay BRW" arm.

The filters are designed so that when no electric field is applied (the off-state), the signal around the central wavelength of 1550 nm launched into the conventional arm, is cross-coupled to the PhC arm over the coupling length L , defined as the beating length for the two lowest supermodes of the coupler:

$$L = \pi/(\beta_2 - \beta_1), \quad (1)$$

where β_1 and β_2 are the propagation constants of the supermodes. Light at all other wavelengths stays in the conventional arm. The central wavelength of the filter is determined by the phase synchronism (transverse resonance) condition [5, 6]. The filter bandwidth $\Delta\lambda_{-3dB}$ is inverse proportional to the coupler length L , and to the differential dispersion σ of the two waveguides in isolation [5]:

$$\Delta\lambda_{-3dB} \approx \frac{0.796\lambda}{L\sigma} \text{ where } \sigma = \frac{d\bar{N}}{d\lambda} - \frac{dN}{d\lambda} \text{ and } \bar{N}, N \text{ effective indices of the respective waveguides.} \quad (2)$$

Since the conventional $\text{GeSiO}_2/\text{SiO}_2$ arm is a low contrast waveguide of weak dispersion, to narrow the bandwidth a given coupler length the dispersion of the other arm should be maximized. Conventional waveguides possible with low index electro-optic materials, such as polymers or liquid crystals, are also low contrast and weakly dispersive. Whereas, in PhC waveguides (including BRW's) where light confinement at frequencies within the photonic band gap is possible for an arbitrarily low index core [7], high dispersion can be achieved by the PhC cladding design. By applying the BRW waveguide as one of the coupler arm we obtained a fourfold bandwidth-length product improvement without an extensive effort on the optimization. The main issue for the further analysis is determination of the tuning range.

3. PERFORMANCE ANALYSIS AND RESULTS

For approximate analysis of the tuning properties we used 1D formalism of Ref. 8, based on the scattering matrix method for stratified media, combined with the effective index method to account for the lateral confinement. In order to determine the tuning range we have analyzed the performance of the filter with respect to the following criteria:

- The cross-coupling to the same mode should occur over the whole tuning range.
- The difference between the propagation constants of the supermodes, determining the coupling length (1), should not vary too much with wavelength since it results in extinction-ratio variation.
- Relative dispersion slopes for the two supermodes should not exhibit strong variation either, so that the filter bandwidth variation is kept within acceptable limits.

For directional couplers there is a well known [6] trade off between the bandwidth $\Delta\lambda_{-3dB}$ and the intrinsic tuning rate $d\lambda/dn$:

$$\frac{d\lambda}{dn} = \frac{1}{A\sigma} = \frac{1}{\sigma} \frac{dN}{dn}, \quad (3)$$

since both scale inverse proportional with the differential dispersion. There is some room though for their simultaneous optimization by minimizing A , the factor not shown in [6]:

$$A(\lambda, n, N) = \frac{N}{n} + \frac{\lambda \sqrt{n^2 - N^2}}{2\pi d n} \frac{\partial \phi}{\partial N}. \quad (4)$$

Where d is the BRW core width, and ϕ is the phase shift under reflection from the Bragg cladding, which can be influenced by the choice of the layer thickness and when applicable, also the layer material. Since N lies in the range of the total internal reflection at the glass/Si interfaces the phase shift strongly depends on N , especially when it is chosen so that the incidence angles are close to the critical one. The simultaneous optimization can also be achieved by increasing the coupler length.

Having the above guidelines in mind we have made a preliminary optimization, where we compromised the bandwidth-length product in favor of the tuning range and its quality. In Fig. 2 we show an example of the tuning rate dependence on the Si layer thickness, for the coupler with a LC overlay (Fig. 1b). The curves are shown for several values of the silica layer thickness. The circle shows the chosen pair of the thicknesses for the Bragg cladding, which allowed increase of the tuning rate at the least degradation of the bandwidth, and of the filter performance over the total tuning range.

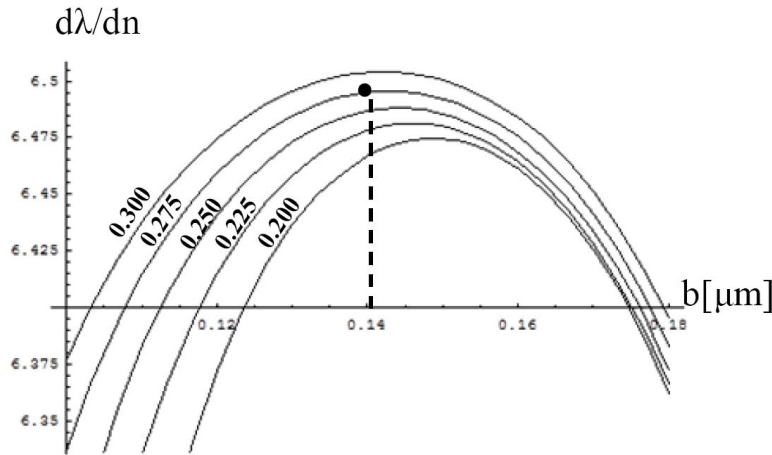


Figure 2. Dependence of the tuning rate on a Si layer thickness b , for different thicknesses of the silica layer. The circle indicates the choice made for the „overlay” case of Fig. 1b.

The latter is illustrated in Fig. 3, where the dispersion curves of the coupler are shown at the off-state and the extremes of the tuning range for both of the considered filters. For coupler 1a, the variations of the coupling length (1) over the range 1510 nm – 1589 nm, do not exceed 19%, hence the resulting variations of the amplitude are below 3%. The bandwidth (2) variations from its off-set value of 1.2 nm (at 7.4 mm length) are below 6% over the whole tuning range. For the filter with a LC overlay (Fig. 1b) a slightly better performance was obtained, probably because we have put more effort on its optimization.

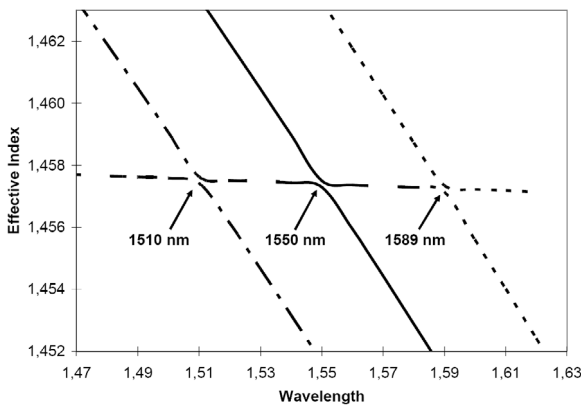


Figure 3a. Supermode dispersion at the off-state (1550 nm) and the extremes of the tuning range for $\pm \Delta n 0.006$ ($\pm \Delta E 5 \mu V/m$) for filter (1a).

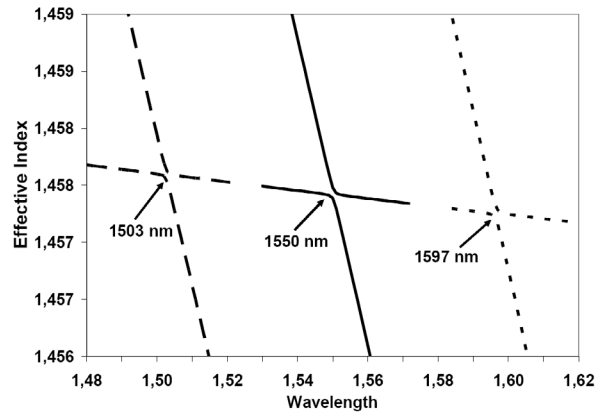


Figure 3b. Supermode dispersion at the off-state (1550 nm) and the extremes of the tuning range for $\pm \Delta n 0.006$ ($\pm \Delta E 5 \mu V/m$) for filter (1b).

The variations of the coupling length from its off-state value of 8.95 mm, and the resulting amplitude variations are in that case below 11% and 1.5%, respectively. Larger tuning range: 1503 nm – 1597 nm was obtained for the same value $\pm 5 \text{ V}/\mu\text{m}$ of the applied field. Although the slope of the dispersion varies a bit more, the resulting bandwidth variations from its off-state value of 1.05 nm are still kept below 11%. Both of the filters are

designed for coupling between the fundamental (0-order) mode in the conventional arm and the first-order mode in the BRW arm. We have checked that the cross-coupling to the higher modes does not occur in a much wider wavelength range than the tuning ranges we show here.

4. SUMMARY

We analysed two design ideas for widely tunable filters based on directional couplers in which one arm is a conventional waveguide and the other is a BRW with a core formed by a commercially available smectic A* liquid crystal. We have checked that by applying BRW instead of a conventional waveguide with a LC core and silica cladding, a fourfold bandwidth narrowing is readily achievable for the same coupler lengths. We showed that tuning ranges of ca 90 nm around the 1.55 μm wavelength under applying the electric field of less than 5 V/ μm , are feasible for both of the considered filters. Both of them show similar performance. Although for the filter with an overlay the bandwidth-length product is slightly worse, 1.05 nm x 8.95 mm to compare with 1.2 nm x 7.4 mm obtained for the full BRW case, it has better stability to the tuning variations, larger tunability range, and is easier to fabricate. We sketched the optimization guidelines and made a preliminary optimization in which the compromise was made between the bandwidth-length product and the tuning rate, with a focus on obtaining a wide tunability range. The presented designs and guidelines are readily applicable for other tuning mechanisms, e.g. where the BRW core width is tuned with MEMS.

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