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Technological Implementation Fabry–Pérot Cavity in Ti:LiNbO₃ Waveguide by FIB

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Abstract—The realization of a Fabry–Pérot (F-P) cavity based on a Ti:LiNbO₃ optical waveguide obtained by using a concept which consists of milling the Bragg gratings (BGs) in the cavity by the focused ion beam technique is shown in this letter. This F-P cavity is formed by two BGs which represent the two reflecting mirrors of the interferometer. The length of the cavity is defined by the distance between the two BGs. Thirty-one peaks and a free spectral range (FSR) = 1.75 nm have been experimentally obtained in the range of wavelengths [1505–1548] nm. The experimental results are in accordance with those of theory. The fabrication process, the experimental results, as well as improvements to increase finesse F and FSR are discussed.

Index Terms—Bragg scattering, Fabry–Pérot (F-P) cavity, focused ion beam, wavelength filtering devices.

I. INTRODUCTION

SINGLE and multiple Fabry–Pérot interferometers have been used as narrowband optical filters for a long time. They have a variety of applications in Telecommunication networks such as in employing wavelength division multiplexing (WDM). Meanwhile, they are used as basis elements to build single-mode lasers, stable frequency references and Dichroic filters which are widely used in optical equipment such as light sources, cameras and astronomical equipment [1], [2].

Many techniques are being used such as thin film multilayer reflectors [3], fiber BGs (photoinduced FBGs) [4], metallic mirrors [5]... to realize two spatially reflectors required by this Fabry–Pérot cavity probe. Devices with outstanding performances can be derived in the case of optical fiber applications, if coatings are deposited directly on the fiber end-faces. Nevertheless, many difficulties can rise up mainly like alignment and packaging. Thus, the use of optical collimation

is required generally with bulk glass elements using dielectric coatings. But, this operation has the disadvantage of increasing the optical losses [6]. In this letter and for the first time, the realization of the F-P cavity on lithium niobate (LN, LiNbO₃) material by FIB is proposed and discussed.

Indeed, the choice of this material is due to what LN is extensively used in integrated optics, owing to its large electro-optical, nonlinear and piezoelectric coefficients. In spite of these advantages, it can be noticed that the micromachining of LN represents a challenging task, due to the well known resistance of the material to standard machining methods like dry or wet etching [7], [8].

Different approaches have been conducted to achieve nanostructures with depths larger than $1\mu\text{m}$. Fields of engineering which use wet etching represent a possible way to fabricate submicrometric holes [9]. However, this method is limited to Z-cut substrates. An alternative method relies on ultrafast laser machining [10]. Yet its application requires the laser spot to be focused near the diffraction limits. The method based on proton exchange followed by Reactive Ion Etching (RIE) or Inductively Coupled-Plasma-RIE (ICP-RIE) has been shown to be applicable [11], [12]. This latter technique was also used for the realization of a F-P intensity modulator with integrated BGs in Ti:LiNbO₃, where BGs are produced in an amorphous Si overlay film, the component was more than 7mm .

Reconfigurable filters are key elements for WDM technologies dedicated to dynamic metro and access networks. Monolithically integrating such as a function on LiNbO₃, a well established material system for electrooptic modulation, would bring additional functionality, efficiency and increased power budget.

The main aim of the present work is the proposal of an efficient technique to realize F-P cavities which rely on BGs etching by Focused Ion Beam on Ti:LiNbO₃ optical waveguide. Comparing with traditional methods, FIB milling has the inducement of a direct etching on the substrate without other additional technological steps. In our previous work, the feasibility of efficient BG reflectors with well reproducible periodicity has been proved by using this method [13], [14].

The first paragraph deals with the different technological steps applied to realize the F-P cavity, giving details on the fabrication of the optical waveguides and the FIB milling of BGs. The evaluation of the various types of optical losses, the measurements of the spectral response, the FSR and the Finesse (F) are presented in the second paragraph. Finally, the next improvements expected in order to increase the F and the

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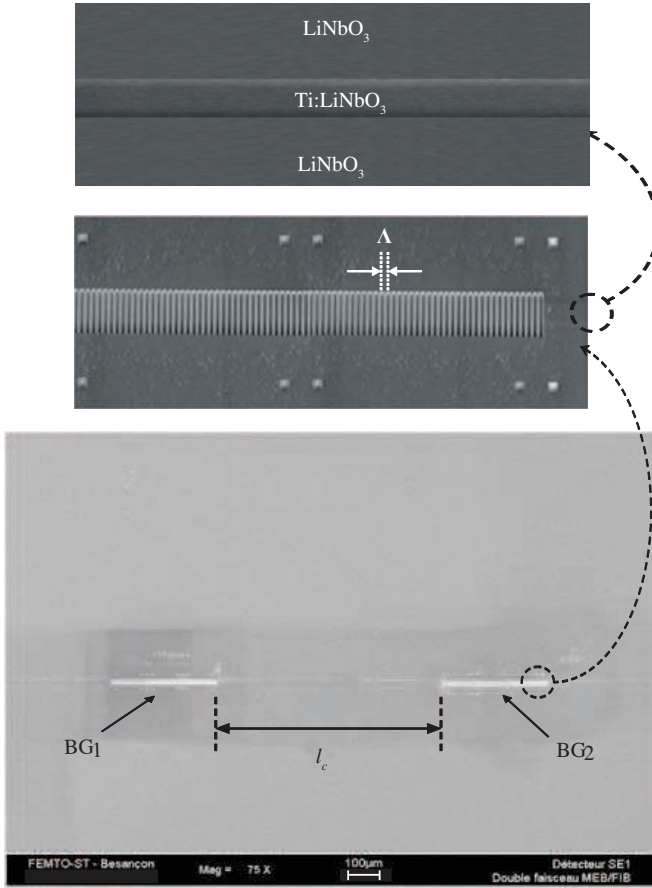


Fig. 1. Two BGs which constitute the F-P cavity and a zoom out of one part of BG_1 and the waveguide Ti:LiNbO₃. Total length of each BG is $L_{BG1} = N_1 \Lambda$ and $L_{BG2} = N_2 \Lambda$. l_c is the cavity length represented by the distance between the BG_1 and BG_2 .

FSR are discussed. Further work is in progress to use the same application in the field of electro-optics taking advantage of the other properties of LN.

II. FABRICATION PROCESS

Ti:LiNbO₃ optical waveguides have been fabricated on a 0.5 mm thick X-cut Y-propagation LiNbO₃ chip. The single-mode optical waveguides in the 1550 nm window have been fabricated by standard diffusion of 80 nm thick and 7 µm wide titanium layers at 1020°C for 9 h. These parameters were chosen in order to obtain the optical mode core as close as possible to the surface while keeping single mode propagation at 1.55 µm. With such experimental parameters, the maximum optical field was estimated to be at 2 µm from the surface, compared to the 3 µm depth that would result from a same Ti-diffusion process for Z-propagation (the mode in Y-propagation is less in depth compared to Z-propagation for an X-cut type LN). Figure 1 (top zoom) illustrates a 7 µm-wide Ti:LiNbO₃ waveguide FIB image.

The next step was devoted to the direct FIB patterning of the substrate. After the deposition of a thin Cr layer by RF sputtering in order to avoid charging effects, the chip was entered into the FIB vacuum chamber, and then exposed to a Ga⁺ liquid metal ion source (LMIS) with ion acceleration energy of 30 keV. This FIB is a dual beam Orsay Physics

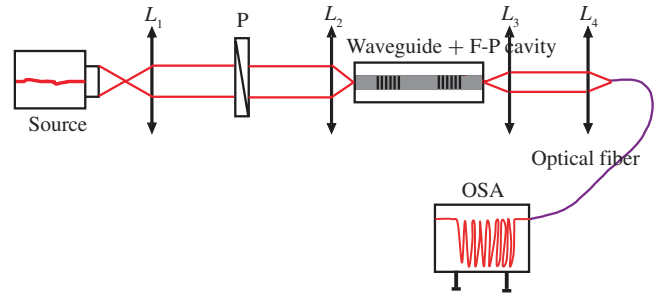


Fig. 2. Experimental setup: source [1550–1560] nm, L_1 , L_2 , L_3 , and L_4 are focusing lenses, P is a Glan polarizer, waveguide containing both BGs which constitute the F-P cavity and optical spectrum analyzer.

Canon 31/LEO4400. The system used to command the beam deflection is a Raith Elphy Quantum 4.0. The pseudo-Gaussian shaped spot size was estimated to be 40 nm on the target. In order to avoid redeposition of the material during the milling, holes were formed by multiple successive exposures (loops). Thus FIB milling was performed on a hole-by-hole basis. This implies a long time process and eventual drift when fabricating very long BGs. Typically for a BG realization, the achievement of a hole with a width of 525 nm, a length of 12 µm and a depth of 3.2 µm requires 130 loops. The FIB parameters were as follows: the dwell time: 0.5 ms, the step size: 10 nm, the probe current was 300 pA and the total exposure time was typically 7 hours for the realization of one BG.

Both BGs have the same period $\Lambda = 1.05 \mu\text{m}$, a total number of periods $N_1 = N_2 = 270$ (the total length of each BG is $L_{BG1} = L_{BG2} = 284 \mu\text{m}$), their etched depths are respectively $l_1 = 3.2 \mu\text{m}$ and $l_2 = 3.3 \mu\text{m}$ and the cavity length represented by the distance between the two Bragg reflectors is $l_c = 540 \mu\text{m}$.

Figure 1 shows an FIB image of the etched BG and an SEM image of an F-P cavity obtained in Ti:LiNbO₃ waveguide by FIB milling.

It is worth noting that the FIB etching process introduces an unavoidable roughness in the BGs surface profile. Furthermore the BGs exhibit a conical etching shape which modifies the expected spectral response. To increase the structure verticality, reactive gases can be added to the milling process, for example by employing XeF₂ gas-assisted gallium ion-beam etching [14].

III. RESULT AND DISCUSSION

We recall that the performances of these BGs are similar to those cited above and had been evaluated in the reference [14]. These performances are of an order of about 99% in reflection associated to bandwidths at mid-height and of about 50 nm.

To assess the spectral response of the BGs, an experimental setup depicted on figure 2 was utilized. It consists in a source whose the wavelength range is in [1500–1560] nm. L_1 , L_2 , L_3 and L_4 are focusing lenses, P is a Glan polarizer to select the appropriate TM mode, and OSA is an optical spectrum analyzer.

At first, the optical characterization of the waveguides is performed. The emphasis is put on the fact that there are several

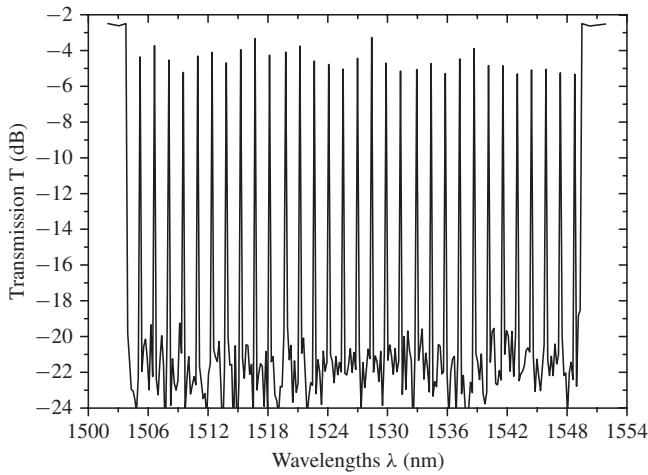


Fig. 3. Fabry-Pérot cavity experimental measured transmittance versus wavelengths and displayed by the mean of the optical spectrum analyzer.

different types of optical losses due to the process insertion, the propagation and to the BGs small non-homogeneities. In the absence of corrugations, the two first types of optical losses can be estimated to be approximately 4.5 dB . Transmissions through a BG and through a standard Ti:LiNbO₃ optical waveguide have been compared. The losses due to the milling technique have been estimated to be between 2 and 2.5 dB .

At the second step of the process, the optical characterization of the F-P cavity was achieved. The experimental results of the transmission through the F-P cavity versus wavelength are given in figure 3. This figure depicts the variations of a classical function of an F-P cavity. It can be observed that 31 peaks have been experimentally obtained in the wavelength range $[1505\text{--}1548]\text{ nm}$ with a reflectivity close to 97% . Each peak has a bandwidth at half maximum $\Delta\lambda = 0.19\text{ nm}$ and the F-P cavity is defined by a finesse $F = 9$ and a Free Spectral Range $FSR = 1.75\text{ nm}$. The experimental results are in high accordance with the theoretical results found by simulations.

Furthermore, in order to increase the values of F and FSR , the reflectivity of the BGs has to be improved either by increasing the etching depth or by rising up the number of periods of each BG. However, the optical losses due to the corrugations might also be increased.

IV. CONCLUSION

The realization of an F-P cavity based on Ti:LiNbO₃ optical waveguide, integrating two spatially separated BGs which are etched by FIB has been demonstrated. Reflectivity coefficient of about 97% , finesse close to 9 and a Free Spectral Range equal to 1.75 nm were obtained. These values can be improved

by making deeper etching or by using very long BG (by increasing the number periods). Work is in progress to take advantage of the electro-optical effect characteristics of lithium niobate, and to develop another method built on using the Vernier effect in order to set a cascade of two F-P cavities.

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