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Tunable filter based on cavity electro-optic modulation for DWDM applications

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In this paper the authors have demonstrated the feasibility and the realization of a wavelength tunable filter with an electro-optic modulation effect realized on a diffused Ti:$LiNbO_3$ waveguide. The two reflectors of the cavity consist in two Bragg's mirrors of identical period $\Lambda = 1.81$ μm and whose total number $N=140$. Both mirrors have been engraved using the Focused Ion Beam technique up to the depths $l_1 = l_2 = 2.7$ μm separated by a distance of $l_c = 500$ μm. We obtained thanks to the electro-optic modulation effect a tunable shift whose value is 0.67 nm in a free spectral range $FSR = 1.59$ nm for a voltage variation neighbouring 60 V. This designed and realized probe will find many DWDM (Dense Wavelength Division Multiplexing) applications.

1. Introduction

The development of the multi-users systems DWDM (Dense Wavelength Division Multiplexing) and all-optical networks have known a growing interest since the last few years. The DWDM technology associated with optical amplification can carry information at very high data rates – Tbit optical, capacities up to hundreds Gbit/s can be achieved on a single fibre over very long distances without the need for signal regeneration [1–3]. In the same time, the need of tunable low cost compact components has considerably increased [4,5]. Following this tendency, a need has arisen which is mainly concerned with the design and the realization of wavelength tunable laser sources able to generate any wavelength in a range that is distributed around 1.55 μm. This is in the order to arrive at the design of an ideal widely wavelength tunable source for future high flow rate WDM applications. It should be noted that the main constraints of this type of probes are the high selectivity of the filter ($F.W.H.M. < 1$ nm) and the tuning interval [6].

A research work has been developed and succeeded in the design and the realization of micro-lasers sources using a low threshold and exploiting the properties of the crystal photonics [7] or taking advantage of slow Bloch's modes having the possibility of controlling the direction of the emission [8]. We can also cite the Micro-Electro-Mechanical VCSELs (MEMs) which remain very complicated to realize [9]. Moreover, the diameters of the active regions of the monolithic probes are generally reduced (< 10 μm) to guarantee a single mode transversal emission this leads to a limitation in output powers.

In this paper we present the following work which is relevant to the previous successful and published experimental realization of Bragg's filters [10–13], of Fabry–Pérrot cavity (F–P) [14], of directional coupling [15,16]. This work will serve as an interesting alternate solution in the field of the realization of integrated components at micro- and nano-scale [17–21]. This proposal is assembling the property of electro-optical modulation in lithium-niobate ($LiNbO_3$, LN) and the ability of the nano-engraving and the nano-fabrication in order to realize such an integrated probe [22–25]. So, this probe consists in the realization of a wavelength tunable Fabry–Pérrot cavity using Bragg's mirrors and the property of electro-optical modulation. This cavity is the essential part and the key of the laser-based sources cited above and has been constructed on a diffused single mode Ti:$LiNbO_3$ waveguide with a range of about 1.55 μm.

In Sections 2–4 we discuss the different steps of the realization, the different measurements operated on the probe and the yielded results and we also discuss the perspectives for further work which addresses cavities in cascade with the Vernier effect in order to improve and increase the tunable range of the component.

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2. Sample type choice

An electro-optic effect is a change in the optical properties of a material in response to an electric field that varies slowly compared with the frequency of light. This effect is due to a non-linear contribution of the polarization. This non-linearity resides in the appearance of the non-linear dielectric susceptibilities of order two χ^2 which leads to a linear electro-optical effect called the Pockels which occurs only in the isotropic media or media with inversion symmetry and also in the appearance non-linear electro-optical susceptibilities of order three χ^3 which leads to a quadratic electro-optical effect called the Kerr effect. It is worth noting that in the case of lithium niobate, the prevailing electro-optical effect is the Pockels effect, the Kerr effect remains negligible. The electro-optical effect itself consists in modifying the medium refraction index by the application of an external electrical field. This variation of the refraction index can be expressed by the following equation:

$$n_{eff}^{EO} = n_{eff} + \Delta n_{eff}^{EO} \tag{1}$$

with

$$\Delta n_{o/e}^{EO} = -\frac{1}{2} r E n_{o/e}^3 \tag{2}$$

where r is the electro-optical coefficient involved in the tensor r_{ij} and E is the applied electric field.

By multiplying both members of Eq. (1) by 2Λ, and considering the general Bragg grating (BG) equation of period Λ [12], we can then derive

$$2n_{eff}^{EO}\Lambda = m\lambda_B + m\Delta\lambda_B \tag{3}$$

where λ_B is the reflected BG wavelength and m is the Bragg order.

From the previous equation, it can be observed that the electro-optic effect is traduced at the spectrum level by a small shift $\Delta\lambda_B$ around the wavelength λ_B and hence allows the tuning of the wavelength in the specified range. The tuning mentioned above can be more interesting and significant if the shifting of the wavelength from a central value is high enough.

From Eq. (2), it can be seen that the index variation can be important by increasing the value of the first parameter which is here the electric field applied thanks to the presence of a voltage V between two electrodes separated by a distance d. This applied electric field is given by $E = V/d$. Furthermore, the electric field increase can be achieved by increasing the voltage (one should pay attention to the Break-Down-Voltage) or by diminishing the distance d. The second parameter that derives from Eq. (2) is the electro-optic coefficient which can also increase the wavelength tuning range. This coefficient depends on essentially the choice of the $LiNbO_3$ sample, that is to say the choice of the cut, the choice of the propagation and the polarization. However according to the literature [27–29], the highest coefficient of the electro-optic tensor $[r_{ij}]$ is r_{33}. So, it is preferable to choose the best adapted configuration to this coefficient. Table 1 summarizes both the possible configurations in the case of the lithium-niobate, with a wavevector $\vec{k}$ perpendicular to the electrical field. The other configurations are based on other electro-optic coefficients which are different from r_{33}.

Fig. 1 represents the configuration that we have chosen in our application to obtain the coefficient r_{33} (X-cut, Y-propagation and $\overrightarrow{TE}$ polarization).

3. Fabrication process

Thanks to the mastering of the design and the fabrication of the BGs today, widely spread throughout the literature, we have

Table 1
The two possible configurations in the case where the two electrodes are applied parallel to the propagation axis and with a wavevector $\vec{k}$ perpendicular to the electric field $\vec{E}$.

Cut	Propagation	Polarization	$\vec{E}$, $\vec{c}$	r_{ij}
X	Y	$\overrightarrow{TE}$	$\vec{E} \parallel \vec{c}$	r_{33}
Y	X	$\overrightarrow{TE}$	$\vec{E} \parallel \vec{c}$	r_{33}

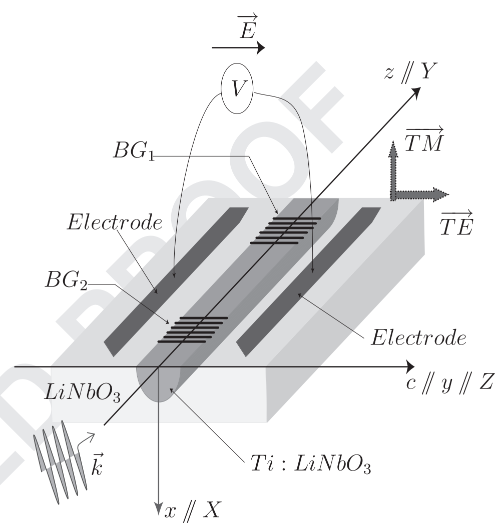

Fig. 1. Two X-cut, Y-propagation configuration schemes with: (i) $\overrightarrow{TE}$ polarization which has the r_{33} electro-optic coefficient that has to be chosen. (ii) $\overrightarrow{TM}$ polarization, r_{13} is the chosen coefficient. In this figure (x, y, z), (X, Y, Z) represent respectively the crystallographic axes and the principal axes of LN and $\vec{c}$ is its optical axis.

fabricated a F–P cavity in a waveguide consisting in two Bragg's mirrors. Thus, in this particular case, the distance separating both networks represents the length of the cavity l_c, and the reflection capacities of the respective mirrors are respectively named R_1 and R_2 when the mirrors are respectively named M_1 and M_2 and respective coefficients of reflectivity $\Re_1(\lambda)$ and $\Re_2(\lambda)$.

The structures have been engraved using the Focused Ion Beam (FIB) technique up to depths $l_1 = 2.7$ μm and $l_2 = 2.7$ μm (same depth for both BGs) respectively in a Ti:$LiNbO_3$ waveguide realized by a diffusing at a temperature of about 1020 °C and since a duration process of about 9 h a very thin layer of Ti whose thickness is $\tau = 90$ nm and whose width is $W = 7$ μm on a X-cut and Y-propagation $LiNbO_3$ sample (see Table 1).

The effective index value of the Ti:$LiNbO_3$ waveguide is $n_{eff} = 2.138$. Thus, the period Λ of the Bragg filter has been calculated following the Bragg diffraction equation [11,13], that is

$$\Lambda = \frac{m\lambda_B}{2n_{eff}} \tag{4}$$

where m and λ_B are respectively the order (taken value $m = 5$) and the Bragg wavelength, whereas n_{eff} is the effective index of the propagating mode in the waveguide.

With the above cited values ($m = 5$, $\lambda_B = 1550$ nm, $n_{eff} = 2.138$) and following Eq. (4), the Bragg filter period is then $\Lambda = 1.81$ μm.

Both Bragg structures constituting the resonant cavity have the same period namely $\Lambda_{BG1} = \Lambda_{BG2} = \Lambda_{BG} = 1.81$ μm and an identical total number of periods $N = 140$. Moreover, both BGs are identical and have a total wavelength $L_{BG1} = L_{BG2} = L_{BG} = 254$ μm. The separating distance between both BGs is this which constitutes

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