Performance of Waveguide FPI with Si-on-$LiNbO_3$ Bragg Gratings under Temperature Gradient.

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Abstract. *It was found that temperature gradient induces degradation of spectral selectivity of Fabry-Perot interferometer formed by channel $LiNbO_3$ waveguide with two Bragg gratings, because of gradient-induced grating chirp and refractive index variation along channel.*

Introduction

Grating structures, and in particular Bragg grating structures, display an effective index dependence in the wavelength of operation that has long been used to form sensing elements in integrated-optic planar devices [1]. In designing high-performance Bragg gratings, the key issue is the ability to perturb the index of the guided mode substantially, still without causing excessive radiation loss, thereby facilitating the realization of compact gratings with high reflectivity. In achieving high-reflectance gratings, a trade-off seems to exist between the process complexity and highest possible reflectivity of the grating. For instance, the high refractive index of $LiNbO_3$ potentially enables large perturbation of the mode index. However, the fabrication of high-reflectance gratings via direct etching in this crystal is an extremely difficult task. Bragg gratings in $LiNbO_3$ with drastically improved efficiencies can be achieved by integrating Si and $LiNbO_3$. Silicon overcomes the aforementioned problems associated with the processibility of corrugated waveguides in $LiNbO_3$.

Experimental

In this work, we employ the new fabrication process to make a Si-on-$LiNbO_3$ structure. A thin Si overlay was deposited by e-beam technique on z-cut $LiNbO_3$ samples, containing a set of annealed proton-exchanged (APE) channel waveguides fabricated with a mask aperture ranged from 5.6 to 9.5 μm. These waveguides were single-mode, supporting only TM_0 mode at wavelengths around 1.53μm. Si-film thickness deposited was 40, 60, 100, 120, 150, 180, 200 and 225 nm. A first order grating (Λ = 357.53 nm) pattern was then holographically defined in a photoresist film, on top of the Si overlay.

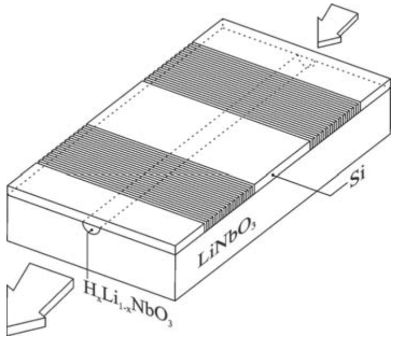

Fig.1. Sketch of waveguide Si-on-$LiNbO_3$ structure.

The delineated photoresist pattern was used as a mask to etch grating corrugations in the Si film to a depth of ≤ 125 nm, by reactive ion etching (RIE). Afterwards, a photoresist mask and wet etching were used to reduce the grating pattern length to cover the two 1.7-mm segments near the middle of the waveguide. 1.5-mm gap inserted between these segments forms waveguide Fabry-Perot interferometer (FPI), fig.1. The necessary electrode pattern was photolithographically delineated in uniform Au-Cr seed layer that was deposited over substrate.

It was found experimentally that the Si grating creates a considerably larger perturbation to the waveguide mode than conventional corrugation, profiled directly on the $LiNbO_3$ waveguide, yet without producing excessive scattering loss. We discover the existence of narrow range of Si overlay thickness from 60 to 150 nm, within which effective index of the TM_0 mode guided into an APE:$LiNbO_3$ channel can be deeply modulated by Si grating, resulting in low-loss grating, even for overlays with a larger length along channel. Outside these intervals, the mode is either absorbed due to the intrinsic loss of Si, or not perturbed by Si grating within very thin overlay. Thus, we have obtained the high grating reflectivity (as high as 0.96, see fig.2) at low-loss propagation, that provide an ideal combination of properties suitable for the fabrication of high-reflectance corrugated waveguide gratings, essential for a number of practical devices [2], in particular, waveguide FPI filters and sensors.

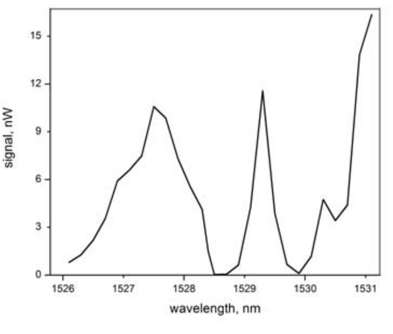

Fig. 2. Transmission spectrum of FPI, utilizing Si-on-$LiNbO_3$ structure. Attenuation of signal in wavelength range between 1526 and 1527.5 nm is caused by sharp decrease of output power of tunable light source at low limit of working range.

Experimental result and discussion

This waveguide FPI has been used by us as electro-optic sensor head in our prototype of optical voltage transducer. The reflection of Bragg gratings is highly wavelength selective, and according to coupled mode analysis it is most efficient when the period Λ satisfies the Bragg condition $\Lambda = \lambda_B/2n$, where λ_B is the free space optical wavelength at the reflectance peak, and n is the effective refractive index of the guided mode [3]. The strong dependence on wavelength for contradirectional coupling makes it possible to tune the wavelength, hence the transmittance through the waveguide FPI, by means of an applied voltage via the electrooptic effect in $LiNbO_3$. When an external voltage V is applied, it induces index changes given by $\Delta n_e = n^3_e V r_{33} \Gamma/(2g)$, where subscript e represents the extraordinary polarization of TM_0 mode, r_{33} is the relevant electrooptic coefficient, g is the separation gap between electrodes, and Γ is the overlap factor between optical and electric fields. The voltage-tuning rate of the wavelength for a

grating can then be expressed as $d\lambda_B/dV = \Lambda n^3_e r_{33}\Gamma/g$, with Λ being the grating period. The switching voltage corresponds to half the spectral width Δλ between the two transmittance minima [3]: $V_s = (\Delta\lambda/2)(d\lambda/dV)^{-1}$. The Bragg wavelength shifts linearly with voltage at a rate of 0.00316 nm/V. Using $n_e = 2.14$ and $r_{33} = 30.8$ pm/V for $LiNbO_3$, a value of 0.6 is calculated from the tuning rate equation for overlap factor, Γ.
High voltage transducers that are based on electro-optic sensor heads have several advantages when compared with their purely electrical counterparts, for example minimal field disturbance, low and high frequency operation, and immunity to electric noise and electromagnetic interference. Furthermore, when using optical fiber pigtailing they allow for both, a simple and compact design as well as excellent electromagnetic isolation. However, it has been found that it is very sensitive to surrounding temperature and, therefore, requires fine temperature stabilization. While the effect of average temperature variation can be compensated by use of a second waveguide FPI as reference, the effect of temperature gradient inside a device box is more dramatic and can't be compensated.
The resonant Bragg wavelength depends on average temperature of an integrated-optical element with waveguide FPI because of termooptic effect in lithium niobate waveguide and thermal expansion of Si film:

$$d\lambda_B/dT = 2\cdot\Lambda\cdot dn/dT + 2\cdot n\cdot d\Lambda/dT \quad (1)$$

Termooptic coefficient for extraordinary refractive index in lithium niobate [4]:

$$dn_e/dT = 3.7\cdot 10^{-5}\ 1/K \quad (2)$$

Change of grating period caused by thermal variation of linear dimension of Si film depends on thermal expansion coefficient of silicon [1]:

$$d\Lambda/dT = 1.41\cdot 10^{-5}\cdot\Lambda_0 = 2.16\cdot 10^{-2}\ \text{nm/K} \quad (3)$$

Hence

$$d\lambda_B/dT = 0.048\ \text{nm/K} \quad (4)$$

These relations (1-3) allow to predict with very good accuracy (<0.01 nm) the temperature dependence of peaks and deeps in transmission spectrum of our waveguide FPI. Therefore these data may be used for precision correction of average temperature effect at electric field sensing.
The measurement of transmission spectra of waveguide FPI at different values of steady-state temperature gradient show gradual degradation of spectral modulation contrast *M* (ratio between output powers at FPI peak and minimum for Bragg gratings transmittance) in transmission spectrum of waveguide FPI. For example, we have observe that $K = 10lgM$ = 18 dB in absence of any marked gradient, but K= 3.5 dB in the field of the strong temperature gradient of 2.8 K/cm. As result, appropriate work of the electric field sensor becomes impossible.
Such a behavior of waveguide FPI can be explained by consideration of gradient-induced grating chirp $C_h(gradT)$ and gradient-induced refractive index variation along

channel. We assume that steady-state gradient induces a linear chirp of the grating period in accordance with (3):

$$\Lambda = \Lambda_0 \cdot (1 + C_h(gradT) \cdot z) \quad (5)$$

In case of a small temperature gradient, we can regard the both gratings being uniform, but having the different periods Λ_1 and Λ_2

$$\Lambda_1 - \Lambda_2 = (d\Lambda/dT) \cdot gradT \cdot L_0 \quad (6)$$

and different values extraordinary refractive index within waveguide areas covered by two Si-gratings:

$$n_1 - n_2 = (dn_e/dT) \cdot gradT \cdot L_0 \quad (7)$$

According to the theory of asymmetric FPI [2,5], the difference between resonant Bragg wavelengths of the two gratings forming FPI $\delta\lambda_B = 2n_1 \cdot \Lambda_1 - 2n_2 \cdot \Lambda_2 \approx 2\{(n_1 - n_2)\Lambda + n(\Lambda_1 - \Lambda_2)\}$ should be theoretically sufficient to induce a significant degradation of waveguide FPI performance even at $gradT \approx 0.3$ K/cм. Experimental test shows that steady-state gradient 0.3 K/cм, created especially by special set-up, induces decrease of maximum output power for FPI peak by factor 1.08 and broadening of FPI peak by 0.012 nm. At electric field sensing experiments, both these effects induce the marked deviation (1.4 %) of sensor response from linear law within sensor dynamic range, which is over 40 dB in absence of temperature gradient. Errors in evaluation of external voltage become more significant in case of randomly oscillating temperature gradient field. Therefore, the fine temperature stabilization, providing low temperature gradient ≤ 0.1 K/cm at our waveguide FPI surface, is required for application in an electric field sensor head.

In conclusion, a FPI intensity modulator has been fabricated and characterized in Si-on-$LiNbO_3$ structure. The Bragg reflectors are produced in an amorphous Si overlay film deposited over annealed proton-exchanged $LiNbO_3$ waveguides. The experimental results demonstrate the prospects of FPI type modulator for voltage sensing. Further improvements can be expected from optimization of the electrode design.

References

[1] T. Conese, R. Tavlykaev, C.P. Hussell and R.V. Ramaswamy, "Finite element analysis of $LiNbO_3$ waveguides with Si overlay", Journal of Lightwave Technology, vol. 16, pp. 1113-1122, 1998.

[2] Yu.O. Barmenkov, D. Zalvidea, S. Torres-Peiró, J.L. Cruz and M.V. Andrés, "Effective length of short Fabry-Perot cavity formed by uniform fiber Bragg gratings", Optics Express, vol. 14, pp. 6394-6399, 2006.

[3] D. Runde and D. Kip, "Holographic reflection filters in channel waveguides for applications as optical sensors and/drop multiplexers", OSA Trends in Optics and Photonics Series, vol. 87, pp. 615-619, 2003.

[4] Lithium Niobate properties, INRAD corp., 2004 - http://www.inrad.com/pdf/Inrad_datasheet_LNB.pdf

[5] S. Pereira and S. LaRochelle, "Field profiles and spectral properties of chirped Bragg grating Fabry-Perot interferometers", Optics Express, vol. 13, pp. 1906-1915, 2005.