A 2 by 2 wavelength tunable Fabry-Perot filter by using an electro-optic polymer film

Xinwan Li (李新碗), Ailun Ye (叶爱伦), Jianping Chen (陈建平), and Guiling Wu (吴龟灵)

State Key Lab on Local Fiber Optical Communication Networks and Advanced Optical Communication Systems, Shanghai Jiaotong University, Shanghai 200030

Received April 1, 2004

A tunable Fabry-Perot (F-P) filter by using electro-optic polymer film is proposed. The electro-optic polymer is alkoxysilane dye (ASD)/SiO_2-TiO_2 hybrid material, whose electro-optic coefficient γ_{33} is about 5 pm/V. The wavelength tuning range of 3.8 nm under 400-V DC voltage and the nonlinear characteristic with the electric field have been obtained via electro-optical properties of polymer. Both of polymer film fabrication and F-P filter design have been introduced. The tunable F-P filter is designed for the application of two-input/two-output port wavelength-selective optical switch. Also, some problems have been discussed in this letter.

OCIS codes: 060.0060, 230.2090, 060.1810, 250.2080.

As the rapid growth of the data communication traffic on optical transport network, the optical switching matrix is becoming the bottleneck of the switching node. Wavelength-selective filters are one of the key components for dense wavelength division multiplexing (DWDM) communication systems and networks, and many functional devices such as optical add-drop multiplexers (OADM) and optical cross-connect (OXC) could be directly constructed. Planar waveguide wavelength filter is one choice for wavelength selective optical switch, such as acousto-optic tunable filter (AOTF)[1]. There are very few papers to study those applications for optical switching by the use of optical filtering technologies. One typical example is the Reconfigurable thin-film filter-based 2×2 add-drop fiber-optic switch structure[2]. However, there are still some problems to be solved for further application on wavelength switching networks, e.g. limited tuning range, sideband crosstalk, tuning speed, and coupling loss with optical fiber, etc. The electro-optic (EO) thin film polymer is proposed to be applied as wavelength selective filter or optical switch. Because of the usage of EO effect of polymer, the tuning/switching response can be high up to 90 GHz[3], and wavelength selective range can also be acceptable for some application system. In this paper, a new kind of 2 by 2 wavelength-tuning optical filter is introduced, the scattering transmission matrix method is used to analysis the characteristics, including the transmission spectrum and wavelength selective range. The design and fabrication of the thin film are given. At last, some experimental results are introduced and some problems to be further improved in future work are discussed.

Fabry-Perot (F-P) optical switch has been presented in 2002[4], where, there are two input ports and two output ports, the F-P spacer material is semiconductor material. Our basic structure of the 2 by 2 wavelength tuning optical filter is based on the F-P filter in the 1550-nm wavelength window as shown in Fig. 1, which applies the alkoxysilane dye (ASD)/SiO_2-TiO_2 hybrid material prepared via sol-gel process. The basic design of the whole wavelength-selective optical switch is composed of $G(HL)^{10}(ITO)(EOP)(ITO)(LH)^{10}G$ stacks, where, G is the glass substrate, $(HL)^{10}$ means ten-pair layer of high and low dielectric constant materials stacks, ITO is the indium tin oxide layer, EOP is the electro-optic polymer layer. This is a typical example of 2 by 2 wavelength-selective optical filter. The working process is as follows: the input port 1 carries serial number of wavelengths, which are limited in one FSR (free space range of F-P cavity), e.g. $\lambda_1, \lambda_2, \cdots, \lambda_n$. There are one or more wavelengths (for example, one wavelength λ_1, two more wavelengths when two more FSR wavelength bands are used) to be selected and transmitted to output port 2, other wavelengths from λ_2 to λ_n except λ_1 are reflected to output port 1; at the same time, the input port 2 carries same number of wavelengths $\lambda_1, \lambda_2, \cdots, \lambda_n$, only the wavelength (e.g. λ_1) selected by F-P filter is transmitted to output port 1, the other wavelengths ($\lambda_2, \cdots, \lambda_n$) are reflected to output port 2. However, due to the use of EO polymer, when the external voltage is applied, the selected wavelength can be tuned to any other wavelength, e.g. $\lambda_2, \cdots, \lambda_n$. So, in fact, it is a one-from-N wavelength-selective optical filter because we only focus one FSR wavelength band. Normally, those DWDM systems use the full C band of the optical fiber transmission windows (e.g. 1530 to 1560 nm). So, it is perfect to design the F-P filter working with the central wavelength at 1530 or 1560 nm and with FSR of 30 nm.

The theoretical analysis is introduced as follows. The characteristic matrix of the EO-polymer is given by[5]

$$M_{\mathrm{POLY}} = \begin{pmatrix} \cos(\delta_{\mathrm{POLY}}) & \frac{i}{\eta_{\mathrm{POLY}}}\sin(\delta_{\mathrm{POLY}}) \\ i\eta_{\mathrm{POLY}}\sin(\delta_{\mathrm{POLY}}) & \cos(\delta_{\mathrm{POLY}}) \end{pmatrix}, \tag{1}$$

where, $\delta_{\mathrm{POLY}} = \frac{2\pi}{\lambda} N_{\mathrm{POLY}} d_{\mathrm{POLY}} \sqrt{1-\left(\frac{N_0\sin(\theta_0)}{N_{\mathrm{POLY}}}\right)^2}$, $\eta_{\mathrm{POLY}} = N_{\mathrm{POLY}}\cdot\cos(\theta)$, for TE waves (or S waves), $\eta_{\mathrm{POLY}} = N_{\mathrm{POLY}}/\cos(\theta)$, for TM waves (or P waves), N_{POLY} is the index of refraction, N_0 is the refractive index of the input material, and θ_0 is incident angle from

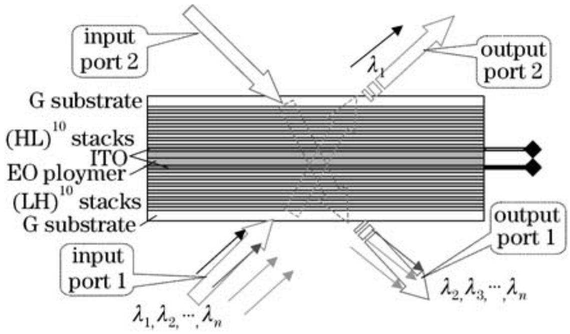

Fig. 1. The basic structure diagram of the 2 by 2 wavelength selective optical filter.

input material. With the above characteristic of EO polymer film inducing to the whole thin film structure as shown in Fig. 1, it is easy to calculate the transmitting optical spectrum from output port 2 and the reflecting optical spectrum from output port 1 modeled in MATLAB. An applied electric modulation filed, E_3, along the direction of the uniaxial nonlinear optical polymer film results in a change of the index of refraction ΔN_i according to[6]

$$\Delta N_i = -\frac{1}{2} N_i^3 r_{i3} E_3 = -\frac{1}{2} N_I^3 r_{i3} \frac{V}{l}, \qquad (2)$$

where the subscript i refers to either principal ordinary or extraordinary quantities. The corresponding linear EO coefficients are r_{13} and r_{33}, respectively. Hence, the simulation of transmitting optical spectrum from output port 2 shows that the wavelength selection and tuning can be easily achieved when the electric field is applied on EO polymer materials. This is because of the change of the index for EO polymer materials.

In this section the preparation and fabrication are presented. The high reflection dielectric thin film layer is fabricated on silica substrate by electrical beam gun, which is composed of high index of refraction (H) and low index of refraction (L) materials periodically (e.g. SiO_2 and TiO_2). In order to apply electrical field, a thin lay of indium tin oxide (ITO) is sputtered above the high reflection layer. Generally, the depth of ITO should be carefully designed because a loss will be caused by the ITO in the F-P filter, in this experiment, the depth is about 50 nm. The top layer is spun with a thin film of the alkoxysilane dye (ASD)/SiO_2-TiO_2 hybrid material prepared via sol-gel process. ASD/SiO_2-TiO_2 is a kind of EO polymer materials, and it is also regarded as the active materials in our F-P filter. The depth of this EO polymer film is 10 μm by choosing the spinning speed and available concentration of EO polymer.

A pair of the above units is arranged in parallel, and let the spacing between the two units as near as possible in order to get a high poling electrical field. In this experiment, the depth of the EO polymer film is 20 μm and the index of refraction is 1.622 at 1550-nm wavelength band. When it is poled with an electric field of 4 V/μm (400 voltages crossing the 109 μm), the EO coefficient of this polymer is about 5 pm/V. The experimental measurement of the EO coefficient has been studied in our group[7]. The optical fiber Mach-Zehnder (M-Z) interference method has been used and proved to be effective.

In this experiment, we have investigated changes of the filter characteristics by parallel plate poling field method, and demonstrated wavelength tuning range about 3.8 nm as shown in Fig. 2. We use Anritsu optical spectrum analyzer MS96A and white light source to measure the transmission spectrum of the filter. Figure 2(a) shows the optical spectrum when zero voltage applies to the electrodes, and Fig. 2(b) shows the optical spectrum when 400 voltage applies to them. From Fig. 2, it can be seen that there are some small modulated peaks on the transmission spectrum, this is because of the Fresnel reflection on the glass substrate. Both of two Fresnel reflection will cause interference. It can be solved by coating an antireflection layer on the glass substrate. By the way, the effective spacing of the F-P is 20.1 μm, including the depth of two EO polymer thin film and depth of ITO layer. The reflection of the F-P mirror is measured 99% at 1550-nm wavelength. Further, we find the relationship

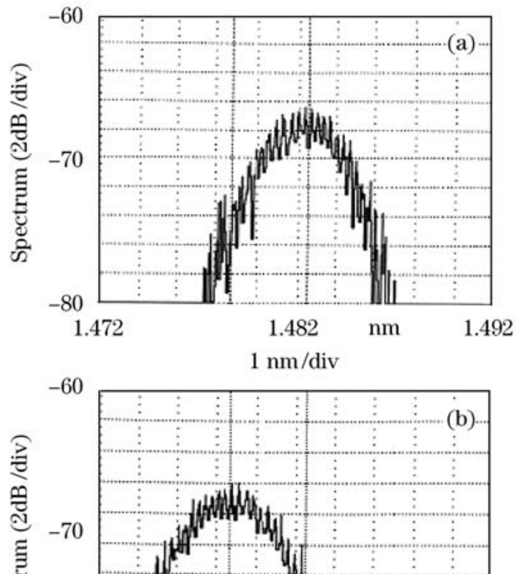

Fig. 2. The optical spectrum when (a) zero voltage, (b) 400 V applied to the electrodes.

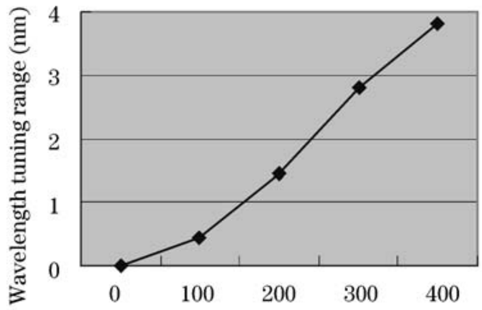

Fig. 3. The relationship between the wavelength-selective range and applied voltage.

of wavelength tuning range depending on the applied voltage as shown in Fig. 3. It shows that the relationship between the wavelength-selective range and applied voltage is not linear. According to Eq. (2), the change of the index of refraction is linear to the voltage applied in the EO polymer thin film, however, the peak wavelength of the F-P cavity will depend on both of refractive index and the operating wavelength, etc.. Especially, we find that the poling effect in the cavity will also cause some additional refractive index change in the EO polymer. It need further theoretically and experimentally study on it.

From both the experimental and theoretical analysis, we find the further work to be improved, for example, the high reflection thin film structure to be redesigned for decreasing the full-width at half-maximum (FWHM). Although we have designed the film structure at 1550-nm window, however, the measurement spectrum is shifted toward short wavelength. There are at least two factors: one is the tilted incident of light, another is the loss of the cavity that is too high. Because the power of white light source is lower, so, the peak wavelength of the F-P filter around 1550-nm wavelength cannot be detected due to the too high reflection of the mirror. So, we have to move our observation window from 1550 to 1480 nm at one free spacing range (FSR) step. The poling field should be increased up to 100 V/μm for increasing the EO efficient of the polymer, and also the anti-coating (AR) on the silica substrate for smoothing the spectrum shape should be considered due to the Fresnel reflection on the silica substrate surface. By the way, the tuning speed will be measured in further work, and how to decrease the driving voltage is also to be solved for practical application in future.

In conclusion, a kind of fast wavelength-selective optical filter has been proposed. The tuning ability has been realized by using the EO polymer, named ASD/SiO_2-TiO_2 hybrid material, whose EO coefficient γ_{33} is about 5 pm/V. The layered-structure of F-P filter has been presented. The wavelength tuning range reaches 3.8 nm under 400-V DC voltage, and the nonlinear characteristic with the electric field has been obtained via electro-optical properties of polymer. The tunable F-P filter is designed for the application of two-input/two-output port wavelength-selective add/drop optical switch.

This work was supported by the National Science Foundation of China (No. 90204006, 60377013), National "863" Program of China (No. 2001AA122074, 2002AA122022), and Shanghai Science and Technology Committee Project (No. 012261022, 022261001, 036105009). X. Lin's e-mail address is lixinwan@ieee.org.

References

1. D. A. Smith, R. S. Chakravarthy, Z. Y. Bao, J. E. Baran, J. L. Jackel, A. d'Alessandro, D. J. Fritz, S. H. Huang, X. Y. Zou, S.-M. Hwang, A. E. Willner, and K. D. Li, J. Lightwave Technol. **14,** 1005 (1996).
2. W. H. Wong and E. Y. B. Pun, in *Proceedings of OFC'2002* 18 (2002).
3. S. Sumriddetchkajorn and K. Chaitavon, IEEE Photon. Technol. Lett. **15,** 930 (2003).
4. R. W. Adair, G. A. Clarke, B. P. Hichwa, C. Iaconis, D. G. Jensen, S. C. Olson, J. W. Seeser, and B. L. Swaby, "Fabry-Perot optical switch" United States Patent us6,490,381B1 (2002).
5. H. A. Macleod, *Thin Film Optical Filters* (Institute of Physics Publishing, Bristol and Philadelphia, 1986) pp. 179—209.
6. C. A. Eldering, A. Knoesen, and S. T. Kowei, J. Appl. Phys. **69,** 3676 (1991).
7. J. X. Hong, J. P. Chen, Y. P. Wang, and X. W. Li, J. Polymer Research (to be published).