Optics Communications 282 (2009) 3052–3054

Contents lists available at ScienceDirect

Optics Communications

journal homepage: www.elsevier.com/locate/optcom

Polarization independent birefringent Fabry–Perot etalon having polarization conversion mirrors

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ARTICLE INFO

Article history:
Received 9 January 2009
Received in revised form 19 March 2009
Accepted 17 April 2009

ABSTRACT

Polarization independent operation of birefringent Fabry–Perot etalon is proposed using polarization conversion mirrors (PCMs) as the cavity mirrors. PCMs, such as Faraday mirrors, rotate the polarization plane by 90° upon reflection thus allowing the same phase accumulation for the two eigenwaves after a roundtrip inside the cavity. Based on that when the cavity is filled with an electrooptic material such as a liquid crystal, polarization independent tunable filtering is obtained.

Tunable filters are highly desired for many applications such as in optical spectroscopy and hyperspectral imaging [1], color generation [2], optical telecommunication [3,4], frequency domain optical coherence tomography [5] and other optical noninvasive medical diagnostic techniques [6]. Compactness, polarization independence, high dynamic range, narrow bandwidth and tuning speed are among the properties desired in such filters particularly for optical telecommunication and biomedical optical imaging applications for diagnosing a variety of diseases such as the use of hyperspectral imaging of the eye retina for blood glucose measurement using multiple wavelengths [7]. A fast tunable filter is ideal for such applications to allow grabbing multiple images before the eye blinks. The use of liquid crystals in Fabry–Perot (FP) cavity has been demonstrated by several investigators [3,4,8–10] to give fast tunable filtering because only a thin layer up to few micrometers is required inside the cavity. One of the drawbacks of this configuration however is the polarization dependence which requires the use of polarizers and thus cuts the light throughput by 50% and makes the system expensive. There exist several concepts to avoid the polarization sensitivity of FP tunable filters such as the use of double pass [11], twisted nematics [12], two filters in tandem [13], the use of quarter waveplates (QWP) on the mirrors [14,15] and by splitting the beam into two orthogonal polarizations [16]. In this paper the use of polarization conversion mirrors is proposed as the cavity mirrors showing that they cancel the polarization dependence when the intracavity medium is birefringent. The use of QWPs adjacent to the cavity mirrors [14,15] form a special case of polarization reflection mirrors, while the concept proposed here is more general since PCMs can be made from a wide variety of anisotropic and diffractive structures.

A polarization conversion mirror (PCM) is a mirror that rotates the plane of polarization of incident linearly polarized light by 90° upon reflection. The classical example of such a mirror is the Faraday mirror which consists of a Faraday medium with its axis oriented at 45° with respect to the incident polarization under an external magnetic field. Upon the forward pass the polarization plane is rotated by 45° and during the backward pass additional 45° rotation is attained. Another well known PCM is the combination of a quarter waveplate (QWP) and isotropic mirror with the axis of the QWP oriented at 45° to the incident linear polarization. Upon the forward passage the light becomes circularly polarized (Right R or Left L) and upon reflection from the isotropic mirror its helicity is reversed so that during the backward passage through the QWP it becomes linearly polarized but orthogonal to the incident polarization. The use of this special case of PCM for polarization insensitive tunable FP was demonstrated in Refs. [14,15]. In the present work I propose the use of general PCM for this purpose not limited to the special case of a QWP on a mirror. More modern PCM concepts involve a variety of diffractive structures [17–20], anisotropic photonic crystals [21], and the first order selective reflection peak from chiral smectic liquid crystals at oblique incidence [22]. Using a one dimensional stack of anisotropic layers the PCM operation was shown [21] over a wide angular range near the condition for omnidirectional reflection. The Jones matrix for a general PCM can be expressed as follows:

$$W_{pcm} = r\begin{pmatrix} 0 & \pm 1 \\ 1 & 0 \end{pmatrix}, \tag{1}$$

where r is the amplitude reflection coefficient of the mirror and the ± signs take care of the cases when there is a π phase shift between the two orthogonal polarizations upon reflection. For the Faraday mirror the plus sign is usually used. The most important fact in Eq. (1) is the fact that the matrix is off diagonal and the ± signs

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doi:10.1016/j.optcom.2009.04.044

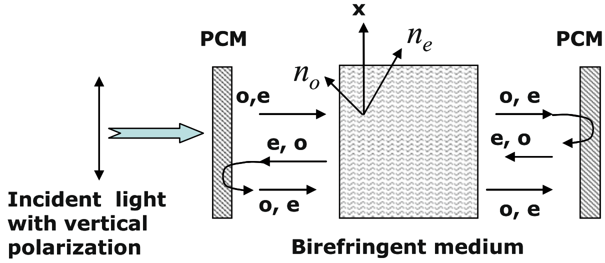

Fig. 1. Schematic of the polarization independent FP with birefringent intracavity medium showing the polarization conversions of incident vertically polarized light.

do not change the final consequences. For consistency reasons we use the minus sign in this article.

Let us consider the birefringent FP structure shown in Fig. 1 where the light with wavelength λ impinges from the left side at normal incidence. The birefringent medium (BM) has ordinary and extraordinary refractive indices $n_{o,e}$ and thickness d. The slow axis of the intracavity BM is oriented at 45° with respect to the x-axis. Consider the case when the incident polarization is along the x-axis which excites the ordinary (o-wave) and the extraordinary (e-wave) waves in the BM medium and each accumulates a phase change $\varphi_{o,e} = 2\pi n_{o,e} d/\lambda$ upon a single forward passage. Upon reflection off the PCM the e-wave (or o-wave) is rotated by 90° and so becomes the o-wave (or e-wave) during the subsequent backward passage through the BM. Hence during a single roundtrip of the beam in the cavity the two eigenwaves accumulated the same phase change $\varphi_{roundtrip} = \varphi_o + \varphi_e$. Formally all this can be shown by writing down the Jones matrix for the round trip, that is, for the three components: BM at 45°, PCM and BM at 45°. The round trip Jones matrix is:

$$W_{roundtrip} = r^2 \exp(-i\varphi_{roundtrip}) \begin{pmatrix} 0 & -1 \\ 1 & 0 \end{pmatrix} \begin{pmatrix} e^{-i\Gamma/2} & 0 \\ 0 & e^{i\Gamma/2} \end{pmatrix} \begin{pmatrix} 0 & -1 \\ 1 & 0 \end{pmatrix} \times \begin{pmatrix} e^{-i\Gamma/2} & 0 \\ 0 & e^{i\Gamma/2} \end{pmatrix}, \tag{2}$$

where $\Gamma = 2\pi(n_e - n_o)d/\lambda$ is the phase retardation. After multiplication the final result is:

$$W_{roundtrip} = -r^2 \exp(-i\varphi_{roundtrip}) \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix}, \tag{3}$$

Hence the round trip Jones matrix is the unity matrix multiplied by a common phase factor which is simply the phase accumulated during a round trip. Similar considerations can be drawn when the incident polarization is along the y-axis. This is the essence of the proposed concept for a polarization independent FP tunable filter. Since the condition for a FP resonance is to have the round trip phase equals multiples of 2π, we get the same resonance wavelengths for the e-wave and the o-wave, that is one single resonance peak in transmission and no splitting due to the birefringence. The location of the resonances is determined by $\lambda_m = (n_e + n_o)d/m$ where m is an integer. In electrooptic crystals such as homogeneously aligned liquid crystals, n_e is a function of an applied electric field, magnetic field or temperature, hence polarization independent tunable filters can be built based on this concept.

The question that may be raised now is how the deviation from the ideal polarization conversion affects the performance of the device. Deviation from the ideal situation may be represented by introducing phase retardation upon reflection. The non ideal PCM Jones matrix will then take the form:

$$W_{ni-pcm} = r \begin{pmatrix} 0 & -e^{i\delta} \\ 1 & 0 \end{pmatrix}, \tag{4}$$

where δ is the phase retardation introduced upon reflection. The effect of this phase retardation is to produce elliptic polarization upon reflection. Assuming the incident wave is e-polarized, then due to the non ideal PCM, the two reflection coefficients r_{ee} and r_{eo} do not vanish. The coefficient r_{eo} represents the reflected part that is polarization converted from e-polarization to o-polarization while r_{ee} is a result of the non ideal operation of the PCM. The net result of this situation is that the output of the FP cavity will have some polarization dependence. The two transmission peaks polarized in e or o polarization will be slightly split depending on the introduced phase retardation δ with respect to the roundtrip phase $\varphi_{roundtrip} = \varphi_o + \varphi_e$. To compensate for this, one can change the gap of the cavity to minimize the relative effect of the mirror induced retardation δ. This is demonstrated in Fig. 2 where in (a) the splitting is observed clearly while by varying the gap, the two peaks of the two orthogonal polarizations coincide. The calculation of Fig. 2 was performed using the 4×4 matrix method described elsewhere [22,23]. The coincidence is almost perfect near the central peak because at this wavelength the QWP is ideal. The polarization conversion is ideal at a specific wavelength but deviates from this case for other wavelengths. This means that the bandwidth of the PCM should be wide enough for the polarization independent FP to operate over its dynamic range. The case of a PCM consisting of a combination of a QWP and isotropic mirror is one such example of PCM that is ideal only at a single wavelength. Wideband PCMs are possible using diffractive structures [16–20] and QWPs made of diffractive structures [24–26] and anisotropic photonic crystals [21]. Another important

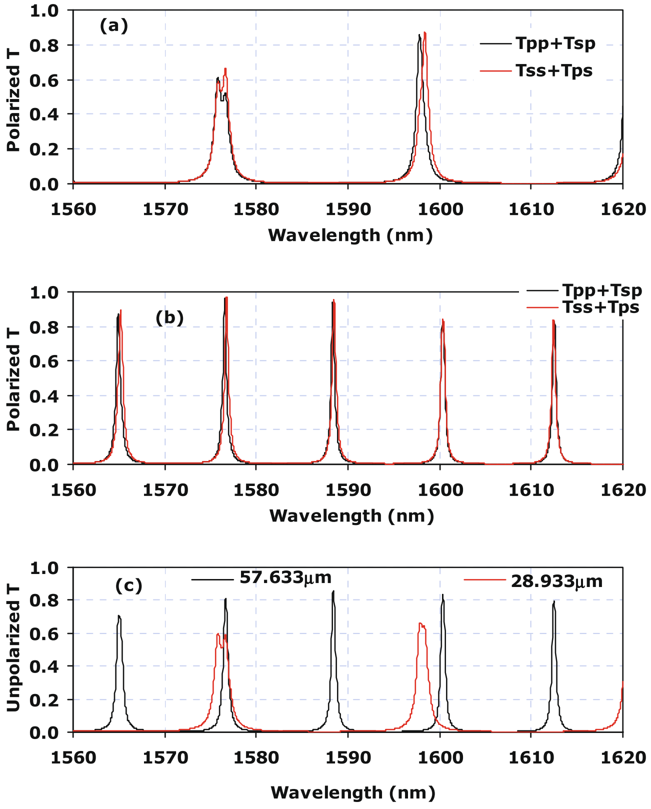

Fig. 2. Transmission through a FP etalon with birefringent material in the cavity and polarization conversion mirrors composed of quarter wave plate and dielectric mirror. (a) and (b) show polarized transmission for cavity gaps of 28.933 μm and 57.633 μm, respectively while (c) shows the unpolarized transmission for both cases. The refractive indices of the birefringent material are: $n_o = 1.55$, $n_e = 1.75$ while the dielectric mirror (with reflectivity ~90% over the whole spectrum) is composed of periodic alternating stack of three periods of SiO_2/Si with indices $n_{SiO_2} = 1.44$, $n_{Si} = 3.34$ and thickness 182.85 nm. The external medium has refractive index 1.45.

fact seen in Fig. 2 is the fact that the transmittance peaks are less than 100% even for unpolarized transmittance. To explain this, note that each curve in Figs. 2a and b is composed of two parts for example for the p-polarized waves (at normal incidence p or s correspond to light polarized along x or y, respectively) it is the sum of T_{pp} and the polarized-converted transmission T_{sp} and similarly for the s-polarization it is $T_{ss} + T_{ps}$. Since these two parts do not exactly coincide, the sum does not result in 100% with the side effect of widening of the resulting peak. A similar argument explains the fact that the unpolarized transmission peaks are less than 100%. The periodic dielectric mirror used in our case is found to introduce phase retardation upon reflection, however it is possible to design mirrors even with dielectric stacks or using achromatic PCMs made of metallic diffraction gratings with 180° phase retardation, which will allow perfect operation of device.

To conclude, a polarization independent operation of FP tunable filters is proposed using cavity mirrors made of polarization conversion mirrors. Such mirrors can be prepared in the form of thin films on glass substrates using anisotropic polymers or subwavelength diffractive structures. This device allows ease of use as no polarizers are required and because of that the light throughput is improved.

Acknowledgement

This work is supported by the ministry of science under “Tasht-iot” funding program.

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