A UNIVERSAL COMPENSATOR FOR POLARIZATION CHANGES INDUCED BY BIREFRINGENCE ON A RETRACING BEAM

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We report a new optical scheme that eliminates birefringence effects on the polarization state of a beam which retraces its path. The operation is based on the symmetry properties induced by a Faraday rotator followed by a mirror on the Poincaré sphere rotations. The entrance and exit polarizations states turn out to be always orthogonal points on the Poincaré sphere. Experiments confirm the theory and point out full remotion of any birefringence effect on the final polarization state. At variance with previous methods, the proposed scheme does not control the exit polarization state but it removes the birefringence change effect at its source. Thus, it behaves on the polarization perturbations as a phase-conjugated mirror does on the phase perturbations.

This work deals with the problem of the control of the state of polarization, SOP, of a laser beam during its propagation in a medium subjected to a birefringence change. Whenever a laser beam is used in an optical instrument the control of the polarization state is an important requirement. In coherent detection, the departure from the full control of SOP causes a reduction of the fringes contrast and constitutes one of the principal noise sources of the detection [1].

The evolution of SOP through a birefringent medium can be useful visualized by means of the Poincaré sphere [2]. A combination of linear and circular birefringence induces a motion of the representative point from the input polarization state $|a\rangle$ toward the final state $|a'\rangle$ through a distinctive path on the Poincaré sphere. When this beam is observed by an optical analyzer, represented by the SOP $|b\rangle$, the transmitted intensity changes as a cosine square of half the angular separation between the two points $|a'\rangle$ and $|b\rangle$ on the Poincaré sphere.

The birefringence of a medium is often subjected to a temporal evolution which produces new paths on the sphere and a difficult predictable exit state $|a'\rangle$. Active and passive solutions have been proposed for the SOP control. A review of these approaches is reported in ref. [3]. Among the active systems worth of mention are the uses of electro-optics and magnetooptics effects, either on free propagating or guided laser beams. In fiber-optics coherent detection, the use of high-birefringent fibers supplies a passive solution to the problem. All these approaches present particular drawbacks, discussed in ref. [3]. In synthesis, it is possible to notice that none of the proposed active approaches attempts to prevent the medium birefringence effect on the exit light SOP. Instead, all are applied to control the final beam SOP brought about by the birefringence evolution. Moreover the use of a high-birefringence fiber offers poor transmissive characteristics and it presents cross-talk between the two polarization channels. Besides it results very expensive.

The aim of this work is to present a novel optical configuration to eliminate the influence of any medium birefringence change on the final SOP of a propagating light beam. The optical configuration behaves like a mirror where the returning beam is always orthogonally polarized with respect to the incoming one, independently of type, value or direction of the birefringence state occurring in the beam propagation.

Consider a path retracing beam through a retarder R as in fig. 1a. The retarder R is characterized by a linear birefringence Δ and by the principal axis rotated Θ to a fixed reference direction. On the other hand, the first of the Jones's equivalence theorems

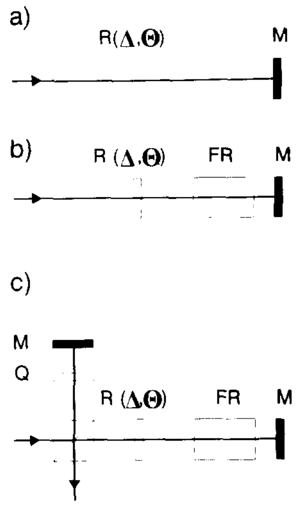

Fig. 1. (a) A retracing beam which crosses the generic retarder R. (b) The proposed optical configuration. FR is a magneto-optics Faraday rotator. (c) An interferometer based on the proposed configuration. Only the Pancharatnam phase is measured when the retarder R rotates or change its birefringence power.

[4] guarantees that this retarder can represent any general combination of retarders and rotators.

In this framework, the exit polarization state $|a'\rangle$, depends on the input state $|a\rangle$ through the general relationship

$$|a'\rangle = [J(\Delta,\Theta)]\ |a\rangle\ , \tag{1}$$

where $[J(\Delta, \Theta)]$ is the unitary operator representing the evolution of the polarization state on the Poincaré sphere. Any change of the state of birefringence of the material will reflect on $[J]$ thus giving different exit states $|a'\rangle$. To remove this unwanted effect the sufficient condition is obtained by imposing to the operator $[J]$ a constant expectation value for the state $|a\rangle$ [5].

Hereinafter a practical method is reported to obtain this condition. Consider fig. 1b, where mirror M is set after a Faraday rotator with rotation power exactly $\pi/4$ for the considered wavelength. The Jones matrix for this "mirrored" Faraday rotator, MF, is

$$[\mathrm{MF}] = \begin{bmatrix} \sqrt{2}/2 & -\sqrt{2}/2 \\ \sqrt{2}/2 & \sqrt{2}/2 \end{bmatrix} \begin{bmatrix} -1 & 0 \\ 0 & 1 \end{bmatrix} \times \begin{bmatrix} \sqrt{2}/2 & \sqrt{2}/2 \\ -\sqrt{2}/2 & \sqrt{2}/2 \end{bmatrix} = \begin{bmatrix} 0 & -1 \\ -1 & 0 \end{bmatrix} . \tag{3}$$

Since a generic retarder R can be expressed [6] by the matrix

$$[R] = \begin{bmatrix} \cos^2\Theta \exp(\mathrm{i}\Delta/2) + \sin^2\Theta \exp(-\mathrm{i}\Delta/2) & \mathrm{i} \sin 2\Theta \sin \Delta/2 \\ \mathrm{i} \sin 2\Theta \sin \Delta/2 & \sin^2\Theta \exp(\mathrm{i}\Delta/2) + \cos^2\Theta \exp(\mathrm{i}\Delta/2) \end{bmatrix} \tag{3}$$

it is easy to demonstrate that the operator $[J]$, for the whole optical circuit, becomes

$$[J] = \begin{bmatrix} 0 & -1 \\ -1 & 0 \end{bmatrix} . \tag{4}$$

The structure of this matrix guarantees that the exit polarization state is always orthogonal to the entrance state. Further properties turn out by calculating the expectation value of $[J]$ for the generic polarization state with components a_x and a_y (complex numbers). It will be

$$\langle a|J|a\rangle = -2a_x a_y\ , \tag{5}$$

therefore the expectation value of $[J]$ for the optical circuit shown in fig. 1b is Δ and Θ independent.

Since retarder $[R]$ represents any possible state of the linear birefringence, the circuit in fig. 1b eliminates any influence of the birefringence changes on the propagating beam SOP.

For the particular case of an entrance linear polarization state, the expression (5) is zero, that is, an orthogonal linear polarized light is recovered.

The obtained results are also visible on the Poincaré sphere and its equatorial projection, fig. 2. Let

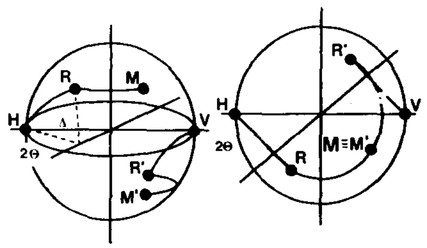

Fig. 2. The Poincaré sphere representation and its equatorial projection. It is shown the evolution of the state-of-polarization of the retracing beam.

us assume for example that the entrance light is horizontally polarized (point H). The presence of retarder R conveys point H to R by means of a rotation around the axis 2Θ by an angle Δ. Half of Faraday rotator effect is produced on the north hemisphere (path RM). The presence of the mirror "reflects" the point M to M′ and the Faraday rotator is now acting on the south hemisphere by moving the point M′ to R′. This point is symmetric to R and by means of a further rotation around the axis 2Θ, it results to be V, i.e. the vertical exit state.

To prove the previous theoretical predictions, an experiment was setup as shown in fig. 3.

The light coming from a polarized HeNe laser source crosses a Foster prism (calcite made with an extinction ratio 10^{-5}) used as polarizer. After the Foster, the light crosses a retarder constituted by a Soleil-Babinet compensator (calcite made) fixed on a rotating platform. The values of Θ and Δ can be chosen with continuity in the range 0, 2π. The beam from the rotating Soleil-Babinet enters the Faraday rotator. To avoid any spurious reflections, the device was custom-tailored in a straight-path configuration. The light coming from the Faraday rotator hits a silver mirror M and comes back. The light is then recollected by the Foster prism and analyzed by a calcite analyzer (Glan-Thompson, calcite made, with extinction ratio 10^{-5}) oriented exactly in the same direction as the polarizer.

If the rotation power of the Faraday rotator is set to exactly $\pi/4$, the intensity transmitted by the analyzer must be only that permitted by the extinction ratio (as predicted by the theory) and no intensity modulation should be observed in correspondence with the rotation of the Soleil-Babinet or with a change of its birefringence power. If the Faraday rotator is "detuned" with respect to the $\pi/4$ value, a modulation in the returned light must be observed in correspondence of the rotation of the Soleil-Babinet.

The results of the measurement, fig. 4, confirm these predictions. Neither angular value nor birefringence power involves any appreciable intensity modulations when the Faraday rotator is corrected tuned. Instead, a detuning of the device causes a "non-universal" behaviour of the compensating scheme: only an appropriate combination of rotation and birefringence power of the Soleil-Babinet produces a returning light cross-polarized.

In summary, a new optical configuration is proposed which, by means of the joint effect of a mirror and a Faraday rotator eliminates any birefringence effects on a beam which retraces its path. On a Poincaré sphere representation, the new configuration permits to "lock" the entrance and exit SOP on two symmetric points, that is on two orthogonal polarized states.

This last property may have relevance on the measurement of the Pancharatnam phase of an optical

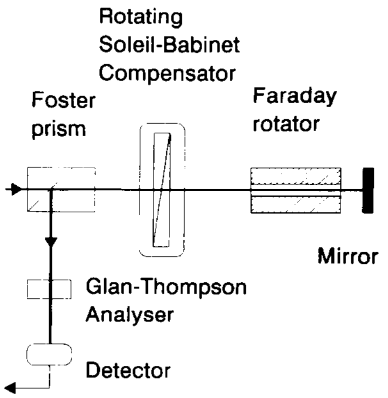

Fig. 3. The experimental setup. The light comes from an HeNe source. The Soleil-Babinet compensator is adjustable either in angular position or in birefringence power. The Faraday rotator is a permanent magneto-optics type.

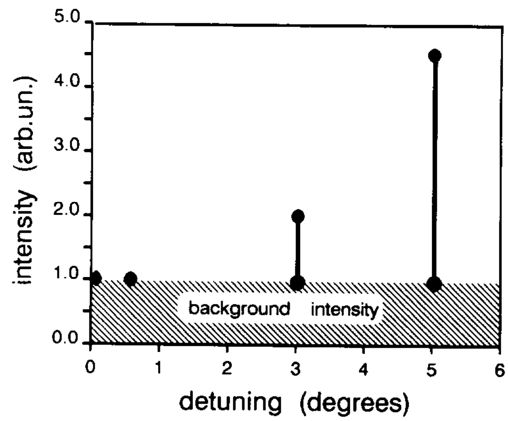

Fig. 4. The collected intensity as function of different "detuning" of the Faraday rotator with respect to 45 degrees. The vertical bars represent the maximum intensity excursion detected in correspondence of a turn angle of the Soleil-Babinet compensator set at different values of birefringence.

system [7]. In fact, if the proposed configuration is applied to an optical interferometer (as in fig. 1c), only the measurement of the geometrical phase evolution is possible, independently of any possible birefringence effects.

Other applications can be found in the fiber-optic interferometric sensors in order to replace the polarization-holding fibers, and in all optical instrumentation where the sensing beam retraces its path. Incidently, the key element of the presented configuration, the Faraday rotator, is already well known in electro-optics as principal component of an "isolator". As consequence, the adoption of the present scheme in instrumentation should be very facilitate.

Finally, the described optical configuration compensates for the birefringence at its source, so distinguishing this approach from any other previously reported. In such as way, the combination of Mirror and Faraday Rotator on polarization perturbations is similar to the Phase Conjugated Mirror effect on phase perturbations.

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