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Performances of a polymer-cholesteric-liquid-crystal output-coupler in Nd-doped fiber lasers

Belkacem Meziane, Chuin Li, Pierre Carette, and Marc Warenghem

Université d'Artois, LPCIA
Rue Jean Souvraz – S.P. 18, 62307 Lens Cedex, France

Michel Mitov

CEMES – CNRS, Liquid Crystal Physics
29, rue Jeanne-Marvig - BP 4347, 31055 Toulouse Cedex 4, France

Abstract: The performances and characteristics of a polymer-cholesteric-liquid-crystal reflector, used as an output coupler in a Nd-doped fiber laser, are presented. We show that a judicious combination of a linear polarizer and a quarter wave plate with the cholesteric coupler allows for a continuous scanning of the output-intensity from zero to a maximum value following the well-known Malus law. The results are shown to be contained in a simple Jones Matrix formalism. The LP-QW-PCLC combination is characterized by a reflection coefficient that can be freely adjusted from 0 to 1 by a simple rotation of the quarter-wave plate.

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OCIS codes: (080.2730) Geometrical optics, matrix methods; (140.3530) Lasers, neodymium; (160.3710) Liquid crystals

References and Links

1. Do Il Chang and al., "Short pulse generation in the mode-locked fibre laser using cholesteric liquid crystal," *Opt. Commun.* **162**, 251-255 (1999).
2. Jae-Cheul Lee and Stephen D. Jacobs, "Design and construction of 1064-nm liquid-crystal laser cavity end mirrors," *J. Appl. Phys.* **68**, 6523-6525 (1990).
3. C. Li, J. Boyaval, M. Warenghem, and P. Carette, "On the design of a Nd³⁺ doped silica fiber-laser using a cholesteric liquid crystal mirror," *Eur. Phys. J. D* **11**, 449-456 (2000).
4. V. I. Kopp and al., "Low-threshold lasing at the edge of a photonic stop band in cholesteric liquid crystals," *Opt. Lett.* **23**, 1707-1709 (1998).
5. M. Mitov, A. Boudet and P. Sopéna, "From selective to wide-band light reflection: a simple thermal diffusion in a glassy cholesteric liquid crystal," *Eur. Phys. J. B* **8**, 327-330 (1999).
6. A. Lavernhe, M. Mitov, "How to broaden the light reflection band in cholesteric liquid crystals ? A new approach based on polymorphism," *C. Binet and C. Bourgerette, Liq. Cryst.* **28**, 803-807 (2001).
7. H. Hasebe, K. Takeuchi and H. Takatsu, "Properties of novel UV-curable liquid crystals and their retardation films," *J. of the SID* **3/3**, 139-143 (1995).
8. C. Binet, M. Mitov, A. Boudet, M. Mauzac and P. Sopéna, "PDLC-like patterns at the isotropic to cholesteric transition entrapped by *in situ* photopolymerization," *Liq. Cryst.* **26** 1735-1741 (1999).
9. F.-H. Kreuzer, D. Andrejewski, W. Haas, "Cyclic Siloxanes with Mesogenic Side Groups," N. Häberle, G. Riepl and P. Spes, *Mol. Cryst. Liq. Cryst.* **199**, 345-378 (1991).
10. F. Sanchez, B. Meziane, T. Chartier, G. M. Stephan, and P. L. François, "Output-coupling optimization of Nd-doped fiber lasers," *Appl. Optics* **34**, 7674-7679 (1995).
11. C. Elachi and C. Yeh, "Stop bands for optical wave propagation in cholesteric liquid crystals," *J. Opt. Soc. Am.* **63**, 840-842 (1973).
12. Kevin M. Flood and Dwight L. Jaggard, "Band-gap structure for periodic chiral media," *J. Opt. Soc. Am. A* **13**, 1395-1406 (1996).
13. R. C. Jones, "A new calculus for the treatment of optical systems," *J. Opt. Soc. Am.* **31**, 488-502 (1941).

In recent years, the use of Cholesteric Liquid Crystals (CLC) as passive polarizing elements in laser cavities has made its way through [1-4]. CLC materials are characterized by a periodic helical structure yielding important optical properties of selective reflection in wavelength stemming from its tendency to split a linearly polarized incident beam into a right or left-handed circularly polarized reflected component and a transmitted part with an opposite

circular polarization for incident light propagating along the helix axis whose wavelength matches the pitch (repeat distance) of the CLC structure. The handedness corresponds to the sense of the helix. A number of potential applications have been demonstrated with CLC polarizing mirrors:-Short pulse generation in the mode-locked fibre laser, - band gap structures, single-longitudinal mode laser operation, low threshold lasing at the edge of the stop-band of a one-dimensional dye-doped CLC film, broad-band reflectors [1, 4, 5]. All these demonstrations make the CLC material a serious candidate as a one dimensional photonic bang-gap material. This letter presents some preliminary results of an experiment using a Cholesteric-Liquid-Cristal Polymer Network as an output coupler in a Nd-doped fiber laser.

The CLC material is photopolymerizable and crosslinkable and is a mixture of 37.7 wt.% of acrylate nematic monomers [6, 7] with 62.3 wt.% of a CLC polysiloxane [8, 9]. The compounds and the concentration are chosen to obtain a transmission-reflection bandwidth situated around the emission wavelength of the Nd-doped fiber laser at 1.064 μm . For polymerization purposes, 2.0 wt.% of a photoinitiator (Irgacure 907 from Ciba-Geigy) is added. The mixture is sandwiched between two glass plates treated with polyimide in order to induce a planar orientation of molecules and thus a Grandjean texture of the CLC which selectively reflects the light. The cell gap is fixed with Mylar sheets and is equal to about 17 μm as evaluated before filling with a spectrophotometer by using the interference method. The CLC is introduced in the cell at 60°C. The filled cell is kept at this temperature on a heating stage and is irradiated with a UV-light curing system emitting at 365 nm. The power is about 0.5 mW/cm² (measured with a UV intensity meter, UVR-365 from Prolabo). The irradiation time is one hour (30 minutes for each side of the sandwich-cell). Due to the UV-induced polymerization and crosslinking reaction, the fluid CLC becomes a solid CLC polymer network which stores the helical structure at 60°C until the room temperature.

First, the transmission and reflection properties are compared to a standard multi-layer coupler having a reflection-band at the lasing wavelength. It is shown that the static properties of the laser with a CLC mirror as the output coupler exactly match those of a standard 0.5-reflection mirror, when no other optical element is introduced inside the cavity. Full advantage of the polarizing properties of the CLC mirror can be taken from the laser system when a linear-polarizer-and-quarter-wave-plate combination is inserted inside the cavity, in front of the CLC coupler. Such a combination amounts to varying the transmission coefficient of the output coupler between 0 and 1, giving the system the property to deliver an adjustable output power that can be freely modulated by simple rotation of the quarter wave plate around the laser axis. The results presented in this communication are limited to the static side, leaving the dynamical part to a next study.

The experimental setup is typical of fiber laser experiments and is schematically represented in Fig.1. The pump is a Titane Sapphire Laser that allows for pump wavelength scanning in the range 0.7 μm -1.1 μm , with a peak output power around 0.81 μm , allowing to efficiently pump the Nd-ions hosted in the fiber matrix with an available output power up to 1.5W.

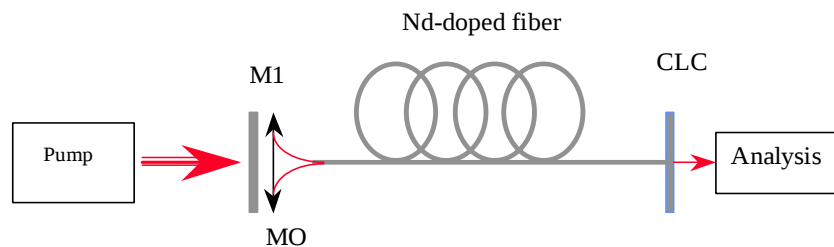


Figure 1 Experimental set-up. Pump: Titane Sapphire laser ($\lambda_p=0.81\mu\text{m}$); M1 : coupling mirror ($R \cong 100\%$ at 1.08 μm , $T \cong 80\%$ at λ_p); MO : microscope objective; CLC: cholesteric liquid crystal mirror.

The Titane Sapphire optically pumps a 15-m-long silica fiber doped with 500 parts in 10^6 Nd^{3+} by weight. Laser oscillation is obtained between mirrors M_1 (reflecting 100% at $1.06\mu m$, while transmitting 80% at λ_p) and the CLC mirror. In order to prevent unwanted optical feedback, an optical isolator is inserted between the pump and mirror M_1 . The pump input power at the fiber laser threshold is typically in the range 25-35 mW.

Figure 2 represents the laser output power versus pump input characteristics obtained both with the CLC and the multi-layer coupler along with the laser characteristic obtained without any output coupler, lasing action taking place between mirror M_1 and the output fiber-end. The crossing of the curves stems from the natural behavior of long fibers to deliver higher output intensities with lower-reflectivity output couplers [10]. As already predicted in Ref [10], optimum output coupling is obtainable without any output mirror, but with only the 4% Fresnel reflectivity of the output fiber-end! While, as expected, higher-reflectivity output couplers result in lower thresholds for laser action, but much lower output intensities at high pump-input powers. These results apply equally well to the CLC mirror as demonstrated in the characteristics of Fig. 2. The linear eigen-polarization modes of the fiber are evenly split into reflected left-handed and transmitted right-handed circularly polarized components. Thus, for linearly polarized light the CLC coupler can be viewed as a standard mirror with 50% reflection coefficient and 50% transmittance, with respect to the laser intensity.

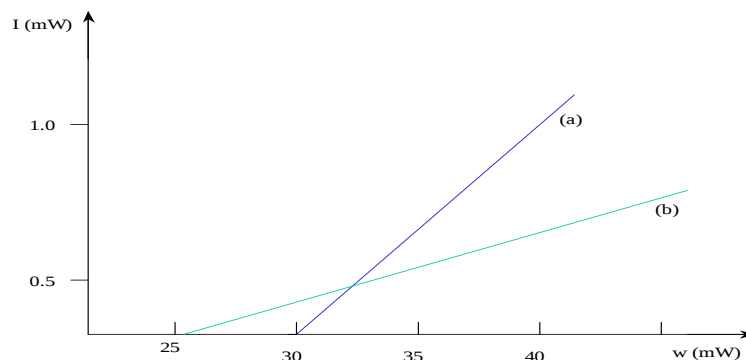


Figure 2 Laser output intensity versus pump input characteristics. Curve (a) was obtained without any output coupler, laser oscillation taking place between mirror M_1 and the fiber end. Curve (b) was obtained both with a 0.5 reflectance dielectric mirror and the CLC coupler. This curve demonstrates that for linearly polarized light, the CLC mirror has a 0.5 reflectivity and 0.5 transmittance. The difference with a dielectric mirror is the circularly induced polarization of the transmitted and reflected light.

Before inserting the CLC mirror in the laser cavity, we performed a series of transmission measurements with a broadband light source delivering unpolarized beams. The results are depicted in Fig. 3.

The band center yielding approximately 50% transmittance appears at $1.064\mu m$. The departure from an exact value stems from Fresnel reflections at the interfaces air-glass (the liquid crystal being sandwiched between two glass plates). In order to check for the handedness of the helical structure of the CLC mirror, a preliminary set up consisting of the combination linear-polarizer-and-quarter wave plate, has been used along with the output signal of the fiber laser at $1.064\mu m$. The method merely consists in finding the orientation of the optical component that completely transmits or completely reflects the laser signal.

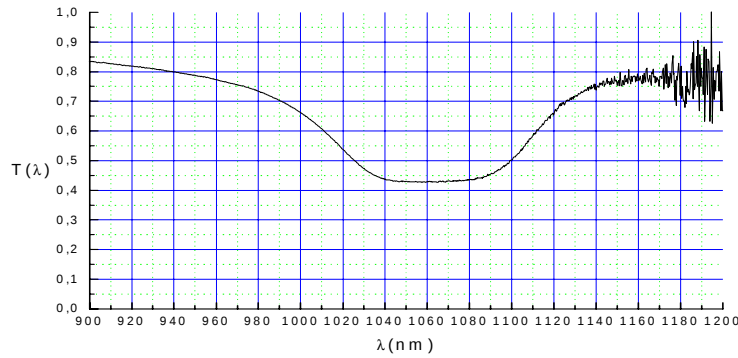


Figure 3 Selective transmission spectrum in the vicinity of 1.06 μm of the CLC mirror obtained with unpolarized light

Before inserting the polarizer and quarter-wave plate inside the cavity, the CLC output coupler was adjusted for optimum lasing efficiency with the help of a chopper inserted between the output fiber-end and the CLC mirror.

A series of measurements with the experimental set-up shown in Fig 4 have been performed. The polarizer inside the cavity, was oriented along one of the fiber birefringence axis (the one with lowest threshold), ensuring a single linearly-polarized mode at any level of excitation. The quarter wave plate is mounted on a graduated holder for quantitative analysis.

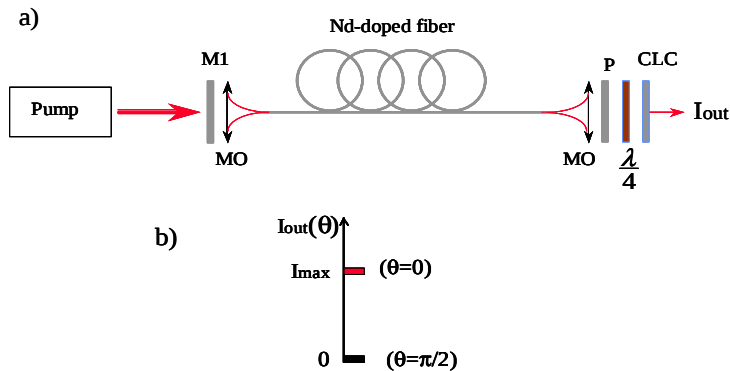


Figure 4 a) Experimental set up for polarization resolved analysis. P: linear polarizer; $\lambda/4$: quarter wave plate at 1.06 μm ; b) Extreme values of the laser output intensity obtained when the quarter-wave-plate axis are oriented at -45° ($I_{\min}$) or $+45^\circ$ ($I_{\max}$) with respect to the axis of the linear polarizer.

Figure 5 represents the output intensity from the CLC mirror with respect to the plate orientation. The curve shows a dependence of the form

$$I = I_0 \cos^2(\theta) \quad (1)$$

$\theta = 90^\circ$ corresponds to the cavity signal circular polarization having the same handedness as the helical sens of the liquid cristal, thus preventing any transmission through the CLC mirror, whereas at $\theta = 0^\circ$, the signal and the liquid crystal have opposite polarization handedness, yielding a completely transparent medium at the lasing wavelength.

The cholesteric liquid crystal is known to be characterized by an index of refraction tensor [11].

$$n(z) = \begin{bmatrix} n + \Delta n \cos(Kz) & -\Delta n \sin(Kz) & 0 \\ \Delta n \sin(Kz) & n - \Delta n \cos(Kz) & 0 \\ 0 & 0 & n_z \end{bmatrix} \quad (2)$$

confering the material circular dichroism in the plane (x, y) for waves propagating along the helix axis z ,

where K is related to the pitch P of the CLC according to $K = \frac{4\pi}{P}$.

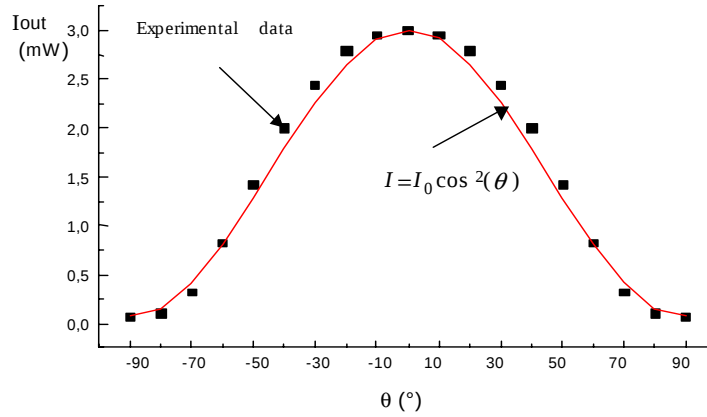


Figure 5 Laser output power as a function of the QWP orientation with respect to the linear polarizer

Wave propagation in such a periodic medium calling for Maxwell-equations allows for the determination of a dispersion relation which contains a range of forbidden solutions for the propagation (stop-band). These stop bands are shown to be directly linked to the pitch of the CLC. Such a formalism is fully developed in the litterature [11, 12]. For the purpose of our paper, we only need a simple formulation leaning on Jones matrix representation [13].

In terms of the Jones matrix formalism, the CLC can be described with the following matrices:

$$\begin{bmatrix} T_R \end{bmatrix} = \frac{1}{2} \begin{pmatrix} 1 & i \\ -i & 1 \end{pmatrix} \quad (3)$$

for a right-handed helix, and

$$\begin{bmatrix} T_L \end{bmatrix} = \frac{1}{2} \begin{pmatrix} 1 & -i \\ i & 1 \end{pmatrix} \quad (4)$$

for a left-handed one.

Any incident linearly polarized wave $\vec{e}$ can be split into a left-handed circularly polarized component and a right handed component, in the form:

$$\vec{e} = e_R \begin{pmatrix} 1 \\ i \end{pmatrix} + e_L \begin{pmatrix} 1 \\ -i \end{pmatrix} \quad (5)$$

Such that the right handed CLC transmits the left-handed component only and the left handed CLC transmits the right-handed component, as can be easily verified with the above Jones matrices :

$$\begin{bmatrix} T_R \end{bmatrix} \vec{e} = \mathbf{e}_L \begin{pmatrix} 1 \\ -i \end{pmatrix}, \quad (6)$$

and

$$\begin{bmatrix} T_L \end{bmatrix} \vec{e} = \mathbf{e}_R \begin{pmatrix} 1 \\ i \end{pmatrix} \quad (7)$$

We also see that

$$\begin{bmatrix} T_R \end{bmatrix} \begin{pmatrix} 1 \\ i \end{pmatrix} = \begin{pmatrix} 0 \\ 0 \end{pmatrix}, \quad (8)$$

preventing any transmission of a right-handed circularly polarized light from a right-handed CLC.

Likewise

$$\begin{bmatrix} T_L \end{bmatrix} \begin{pmatrix} 1 \\ -i \end{pmatrix} = \begin{pmatrix} 0 \\ 0 \end{pmatrix}, \quad (9)$$

preventing any transmission through a left handed CLC of a wave with the same circular polarization as the helical sense of the CLC.

For the reflected wave, the right handed CLC reflects back the right handed component and transmits the left handed one and vice versa.

The reflection properties of the CLC mirror should then be described with Jones matrices, satisfying

$$\begin{bmatrix} R \end{bmatrix} \begin{pmatrix} 1 \\ i \end{pmatrix} = \begin{pmatrix} 1 \\ i \end{pmatrix}, \quad (10)$$

and

$$\begin{bmatrix} R \end{bmatrix} \begin{pmatrix} 1 \\ -i \end{pmatrix} = \begin{pmatrix} 0 \\ 0 \end{pmatrix} \quad (11)$$

Straightforwardly yielding an expression $[R]_{rh}$ for a right-handed CLC and another expression $[R]_{lh}$ for a left-handed CLC.

These Jones Matrix representation for the reflection properties of the CLC mirror are conform to the findings referring to conventional optics, considering the CLC mirror as equivalent to a combination of a quarter waveplate, linear polarizer, and a dielectric mirror [2].

The above Jones matrices describe the transmission and reflection properties of the CLC coupler when the quarter wave plate delivers right or left-handed polarized light, i.e. when the linear polarization axis is oriented at $+45^\circ$ or -45° with respect to the slow axis of the quarter wave plate.

When the quarter wave plate is oriented with an angle φ with respect to one of the above positions, the transmitted wave is elliptically polarized and takes the form

$$\vec{e} = \mathbf{e}_0 \begin{pmatrix} \cos(\varphi) \\ i \sin(\varphi) \end{pmatrix} \quad (12)$$

In this case, the output beam from the CLC coupler writes

$$\vec{\mathbf{e}}_{\text{out}} = \mathbf{e}_0 \begin{bmatrix} 1-i \\ i \end{bmatrix} \begin{pmatrix} \cos(\varphi) \\ i \sin(\varphi) \end{pmatrix} \quad (13)$$

yielding

$$\vec{\mathbf{e}}_{\text{out}} = (\cos(\varphi) + \sin(\varphi)) \mathbf{e}_0 \begin{pmatrix} 1 \\ i \end{pmatrix} \quad (14)$$

That can be written, inferring $\varphi = \theta + \pi/4$,

$$\vec{\mathbf{e}}_{\text{out}} = \mathbf{e}_0 \cos(\theta) \begin{pmatrix} 1 \\ i \end{pmatrix} \quad (15)$$

θ is a measure of the quarterwave plate axes-rotation with respect to the linear polarizer axis.

The intensity output thus follows

$$I_{\text{out}} = \vec{\mathbf{e}}_{\text{out}} \vec{\mathbf{e}}_{\text{out}}^* = I_0 \cos^2(\theta) \quad (16)$$

As can be seen in Fig.5, the experimental data match the theoretical curve fairly well. The small deviations stem from experimental errors owing to the fact that our fiber laser delivers a fluctuating output signal around steady state.

The reflection properties of the CLC mirror associated with a linear polarizer and a quarter wave-plate are, indeed, complementary to the above transmission expression. The LP-QW-CLC combination can be considered as a mirror with a reflexion coefficient following the simple sine law

$$R = \sin^2(\theta) \quad (17)$$

Such an important property should find applications in laser experiments that require a series of precise output couplers without having to call for any specific multilayer dielectric design.

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