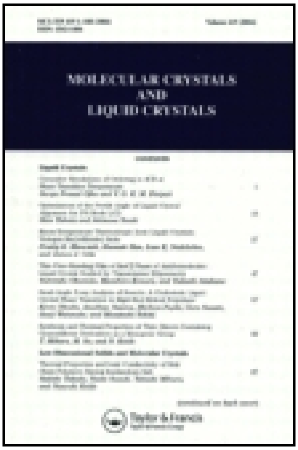

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Ferroelectric liquid crystals (FLC) as light modulators in the stabilization system of a Zeeman laser increase the quality of stabilization due to the high switching speed and make the whole system very compact. We analyze the operation of the optical part of such a stabilization system and derive optimum values of the FLC cell parameters. Properties of available liquid crystals and their temperature dependence are considered as well as, in particular, the influence of a slight ellipticity of the laser radiation.

Keywords: He-Ne Zeeman laser; surface stabilized liquid crystal; frequency stabilization

INTRODUCTION

The two-frequency laser interferometry is a well known technique to measure distance easily and precisely. The main problem with this technique is to have an inexpensive and compact light source that provides two frequency-stabilized wavelengths in the visible range. The He-Ne laser line splitting due to the Zeeman effect is one of the most frequently used techniques to obtain such a source. This technique not only provides two waves with a small frequency shift (about 2 MHz), but also simplifies the stabilization of the laser frequency, since the two frequencies are symmetrically shifted from the center of the atomic emission line. As the two waves have orthogonal polarizations (circularly polarized with opposite directions) they can easily be distinguished. One of the simplest methods of Zeeman laser frequency stabilization is the so-called analogue technique[1], which uses modulation of light intensity in two separate lines. Other techniques use changes of the frequency of two laser lines as an error signal in the laser stabilization loop[2] (known as digital techniques). One of the most interesting methods of Zeeman laser frequency stabilization is the one that uses a nematic liquid crystal cell as a switch for the two laser lines[3]. In that method the two circular polarizations are first transformed into orthogonal linear (by a conventional $\lambda/4$ plate), which are either rotated 90° or not by the LC cell. A polarizer passes only one of these directions to the photodetector. While switching the LC cell an alternating signal is formed at the photodetector with the amplitude proportional to the difference between the circularly polarized intensities coming out of the laser. In such stabilization system no additional modulation of the laser frequency is needed. The main problem is the low switching rate of a nematic liquid crystal (about 1 Hz); thus the frequency stabilization loop is unable to follow rapid changes of the laser frequency due to vibrations. With ferroelectric liquid crystals (FLC) instead of twisted nematic (TN) the switching rate can be substantially increased (up to 1-10 kHz) and satisfactory stabilization can be provided even in a vibrating environment.[4] Another advantage of the FLC cell is that it is able to operate as a $\lambda/4$ plate which reduces the number of necessary optical elements. On the other hand, ferroelectric liquid crystals are very different from nematics and the cell structures are often very complex. In TN cells the molecules are reoriented by the electric field from planar alignment to homeotropic, while in ferroelectric cells the molecules are switched between two stable orientations in-plane with the cell substrates. In the mode best adapted for Zeeman laser stabilization (using C* materials with tilt angle of 45 degrees) the optic axes of these states are orthogonal to each other, but with available materials tending to chevron layer structures, the ideal state is hard to achieve in practice. Furthermore, the orientation of the optic axes is determined by the treatment of the aligning surfaces, together with the molecular tilt in the smectic layers. The molecular tilt is more or less temperature dependent and the switching angle therefore also varies with temperature. This should be taken into account, because the operating temperature in the laser can be as high as 50°C. Also with increase of temperature the birefringence of the liquid crystal is reduced and the phase retardation of the modulator may then substantially deviate from $\lambda/4$. Finally, $\lambda/4$ is the optimum retardation only in the case of circular polarization of the outgoing radiation, and the value will be different if this radiation is elliptically polarized.

These specific features require a detailed analysis of the stabilization system of the Zeeman laser when an FLC is used as polarization switching element.

ANALYSIS

Circular output polarization

Let us consider the principle of stabilization of a Zeeman laser assuming first ideal conditions. We start with the approximation that the laser emits two circularly polarized light waves with opposite handedness and that their frequencies are sufficiently different such that the interference of these light waves can be neglected (the frequency difference is in the range of 2 MHz, while the FLC switching frequency is 1-3 kHz, so beating can be averaged over the time when FLC stays in one state). We shall, thus, consider propagation of each light wave through the FLC cell independently. This simplifies the formulas and enables analysis of analytic expressions.

Assuming the SSFLC cell equivalent to a birefringent plate with fast axis perpendicular to the FLC director, its optical phase retardation is $2\pi\Delta nd/\lambda$ (Δn is the birefringence of the liquid crystal, d its thickness, and λ the light wavelength). Figure 1 sketches the FLC director positions in both stabilized states at the cell surface in the general case of asymmetric switching, that is for $\theta_1 \neq \theta_2$, θ_1 and θ_2 denoting the angles formed by the FLC director with the polarizer axis, respectively. $\theta_1 + \theta_2$ equals the FLC cone aperture.

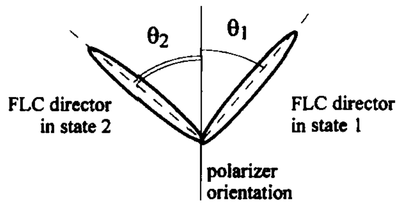

FIGURE 1. Schematic representation of SSFLC director orientations in both stabilized states.

The transmission intensity of circular polarized light through an SSFLC birefringent plate and a vertical ideal polarizer can be written as

$$T_1^R = 0.5\ (1 + \sin 2\theta_1 \sin 2\pi \Delta n d/\lambda) \tag{1}$$

for the right-hand polarized input light, and

$$T_1^L = 0.5\ (1 - \sin 2\theta_1 \sin 2\pi \Delta n d/\lambda) \tag{2}$$

for the left-hand polarized input light with the cell in state 1. In the case of state 2 we have:

$$T_2^R = 0.5\ (1 - \sin 2\theta_2 \sin 2\pi \Delta n d/\lambda) \tag{3}$$

$$T_2^L = 0.5\ (1 + \sin 2\theta_2 \sin 2\pi \Delta n d/\lambda) \tag{4}$$

If we denote F_R and F_L the intensities of two beams coming out of the Zeeman laser, which are right- and left-hand polarized, respectively, the total intensities I_1 and I_2 detected at the output of the vertical polarizer for the two cell states 1 and 2 are:

$$I_1 = F_R\, T_1^R + F_L\, T_1^L \tag{5}$$

$$I_2 = F_R T_2^R + F_L T_2^L \quad (6)$$

The value of primary interest for stabilization is the difference between the intensities at the detector in these two states of the SSFLC cell. Therefore:

$$I_\Delta = I_1 - I_2 = 0.5 F_\Delta (\sin 2\theta_1 + \sin 2\theta_2) \sin 2\pi\Delta nd/\lambda \quad (7)$$

Where $F_\Delta = F_R - F_L$. We can quantify the asymmetry of the SSFLC cell in terms of a deviation angle θ_ε and write:

$$\theta_1 = \theta + \theta_\varepsilon \quad \text{and} \quad \theta_2 = \theta - \theta_\varepsilon \quad (8)$$

where θ is the FLC tilt angle (half the cone angle). After inserting (8), the equation (7) can be rewritten:

$$I_\Delta = F_\Delta \sin 2\theta \cos 2\theta_\varepsilon \sin 2\pi\Delta nd/\lambda \quad (9)$$

From this formula one can conclude, that in the ideal Zeeman laser the variation of the intensity due to switching of the liquid crystal between the stable states is proportional to the difference between the intensities of the light waves with right and left polarization. This variation reaches maximum when the liquid crystal thickness corresponds to a $\lambda/4$ plate. Moreover, the proportionality is preserved in cases when the switching angle 2θ deviates from 90° and when the polarizer is not symmetrically oriented with respect to the stable states of the liquid crystal. Hence, we can conclude, that for circular outgoing polarization the stabilization system should operate in a stable mode even with liquid crystals with molecular tilt different from 45°, with deviations of its phase retardation from $\lambda/4$ and with variations of these parameters with temperature.

This analysis illustrates the basic idea of the laser frequency stabilization with a ferroelectric liquid crystal cell. In reality the situation is more complicated, because the output polarization of the laser, due to external factors, may deviate from being circular.

Elliptic output polarization

Let us consider the case where elliptically polarized light is coming out from the resonator. In this case we have light waves of two slightly different frequencies with similar ellipticities, both ellipses being arbitrarily oriented with respect to the resonator, and with opposite handedness. The value of ellipticity (the extent of deviation from circular) and the orientation of the ellipse depend on inhomogenities in the longitudinal magnetic field, on the deviations of the resonator from the ideal and are, in principle, arbitrary. A liquid crystal cell of arbitrary thickness is switched between two states with arbitrary angle between their optic axes, but these states are symmetrically oriented relatively to the polarizer.

Our aim is to find the conditions at which the signal at the detector (its alternating part) depends only on the relative intensity of these two light waves.

Basic formulas

We shall now generalize the derivation from the previous paragraph for circular polarization; formulas (1) - (9). For elliptically polarized light:

$$\bar{E} = \frac{E}{1+e^2}(\bar{k}_1 + ie\bar{k}_2)e^{i(kr+\omega t)} \tag{10}$$

where E is the amplitude of the light wave, e is the ellipticity of the light incident on the birefringent plate (FLC) with optical retardation Δnd and the angle between the long ellipse axis (vector $\bar{k}_1$). The relative orientation of the plate axis is described by the angle φ. After the plate the light is incident on a polarizer oriented at angle θ with respect to the FLC orientation ($\theta_\varepsilon = 0$). The transmission of the system LC cell - polarizer in this case is:

$$T(e,\varphi,\theta) = \frac{1}{1+e^2}(\cos\varphi + i\,e\sin\varphi)\cos\varphi\,\exp\left(\frac{2i\pi n_e d}{\lambda}\right) +$$

$$+ (\cos\varphi - i\,e\sin\varphi)\cos\varphi\,\exp\left(\frac{2i\pi n_e d}{\lambda}\right)^2 \qquad (11)$$

All variants to be considered are obtained from (11) by varying φ and θ, as well as the ellipticity e. Because both elliptic polarizations have different frequencies, their interference is not observed and the outgoing intensity is simply the sum of these two intensities.

The liquid crystal is switched between two states, which are symmetric relative to the polarizer. In state 1 the outgoing intensity is:

$$I_1(F_R,F_L,\varphi,e) = F_R\,T(e,\varphi,\theta) + F_L\,T(-e,\varphi,\theta) \qquad (12)$$

The intensity in the state two can be obtained by replacing φ by φ+2θ and θ by -θ:

$$I_2(F_R,F_L,\varphi,e) = F_R\,T(e,\varphi+2\theta,-\theta) + F_L\,T(-e,\varphi+2\theta,-\theta) \qquad (13)$$

Let us now consider the signal at the detector in the case that the switching angle is different from 90°. Let us assume 60°, which is a quite common case, and a retardation close to $\lambda/4$. If we have two circular waves (ellipticity e = 1) of different intensities (for example, $k = F_L / F_R = 0.6$), the signal at the detector cannot depend on the orientation of the light ellipse and is determined by the ratio of these intensities. This is, however, not the case for elliptically polarized light (see Figure 2).

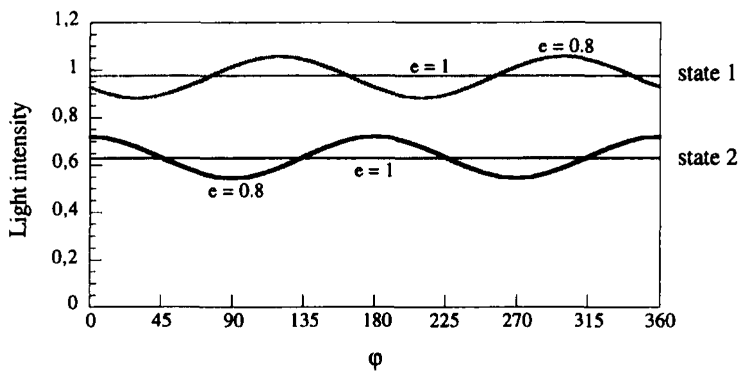

FIGURE 2. Light intensity of the elliptically polarized laser light after passing the LC cell and a polarizer as a function of the orientation of the ellipse relative to the layer normal in the *on* and *off* states. The FLC switching angle equals 60^0, the retardation $\lambda/4$, and the intensities for different elliptic polarizations are taken as $F_R = 1$, $F_L = 0.6$.

The signal occurs to be dependent on the orientation of the ellipse and the deviations are larger the stronger are the deviations of ellipticity from 1. The stabilization system registers the difference of the intensities at the detector in both states,

$$I_\Delta(k,\varphi,e) = I_2(1,k,\varphi,e) - I_1(1,k,\varphi,e) \qquad (14)$$

where $k = F_L / F_R$, and again assuming $F_R = 1$ for convenience.

In the case of circular polarization this expression for $I_\Delta(k,\varphi,e)$ reduces to (9). The orientation of the polarization ellipse and the value of ellipticity are not constant, i.e. may vary during the laser operation. The orientation may be completely arbitrary but the ellipticity is close to 1 (experimentally we found the ellipticity varying between 1 and 0.86; these values are used in the analysis, although they may be different for other lasers).

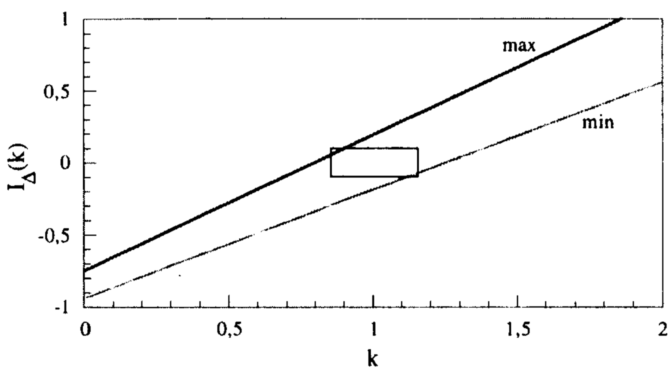

FIGURE 3. Extreme values of the alternating signal at the detector due to FLC switching. The angle of switching is taken to 60^0, the retardation to $\lambda/4$, and the ellipticity to $e = 0.86$. Rectangle shows the range of possible variations due to uncertainty of the ellipticity and orientation of the polarization ellipse.

To analyze the situation, extreme values of intensity difference are important

$$I_\Delta^{min}(k) = \min(I_\Delta(k,\varphi,e))$$

$$I_\Delta^{max}(k) = \max(I_\Delta(k,\varphi,e)) \qquad (15)$$

The interval of variation of the function $I_\Delta(k,\varphi,e)$ due to variations of orientation of the ellipse and its ellipticity is presented in Figure 3. In the case of equal intensities of both polarizations there is uncertainty both in the value and the sign of the signal at the detector. This leads to instability of the whole laser system.

Search for optimum parameters

To optimize the FLC cell parameters one should introduce some function that characterizes the ability of the stabilization system to discriminate the value and the sign of the difference between the intensities of different polarizations. As we have shown, the signal at the detector may vary within the interval $I_\Delta^{min}(k)$ to $I_\Delta^{max}(k)$ due to distortions of the output radiation. The difference of these functions is the uncertainty of the information contained in $I_\Delta(k)$ for the stabilization system. Hence, we may introduce the function

$$F = \frac{0.5 \cdot (I_\Delta^{max}(k) + I_\Delta^{min}(k))}{(1-k)(I_\Delta^{max}(k) - I_\Delta^{min}(k) + \delta)} \qquad (16)$$

where δ characterizes all system instabilities and noise, not connected with the variation of the polarization or intensity of the outgoing light, such as instability of FLC, non-perfect polarizer, instability of the electric scheme, noise of the amplifier e.t.c. We take $\delta = 0.01$.

This function has the sense of 'signal-to-noise' ratio (only relative values are accounted in this formula, because the signal may be amplified any time). The higher function F is, the more precisely the difference of the intensities of different polarization can be measured, and the better laser stabilization can be achieved.

Figure 4 shows F as a function of FLC retardation. For circular polarization of the outgoing light the optimum retardation value (maximal F) is realized for a quarterwave plate, $\Delta nd/\lambda = 0.25$ (and its multiples). But even a small ellipticity changes the situation drastically: the maximum value strongly diminishes and its position shifts towards the half-wave value. The signal at the detector after the quarter-wave plate is only negligibly influenced by the mismatch of the intensities with different polarization. The sources of the alternating signal at the detector cannot be discriminated. This means that an FLC cell with 60^0 switching angle cannot provide reliable stabilization of the laser frequency.

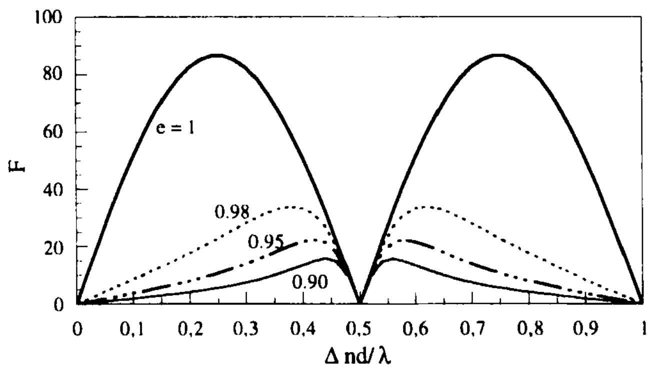

FIGURE 4. Signal-to-noise ratio for the stabilization system at various values of light ellipticity. The switching angle is taken to 60^0.

The optical properties of the FLC cell are determined by its retardation (or more precisely by the ratio retardation to wavelength $\Delta nd/\lambda$) and the switching angle of its optic axis. From Figure 5 it can be seen that the function

F remains sufficiently high and is not strongly influenced by the ellipticity of light only in the case of a cell with switching angle 90^0 and optical thickness close to λ/4. In our experiments we turned to the FLC material CS2005 from Chisso. This mixture has a molecular tilt angle of 43° at 20°C, which decreases to 40° as the temperature increases to 50°C. This results in a switching angle of the cell in the range 86° - 80° for the actual operating temperature of the laser. Simultaneously, the optimum value of the retardation (Δnd/λ) increases from 0.25 to 0.35 and 0.38 (when the switching angle changes from 90° to 86° and 80°, respectively).

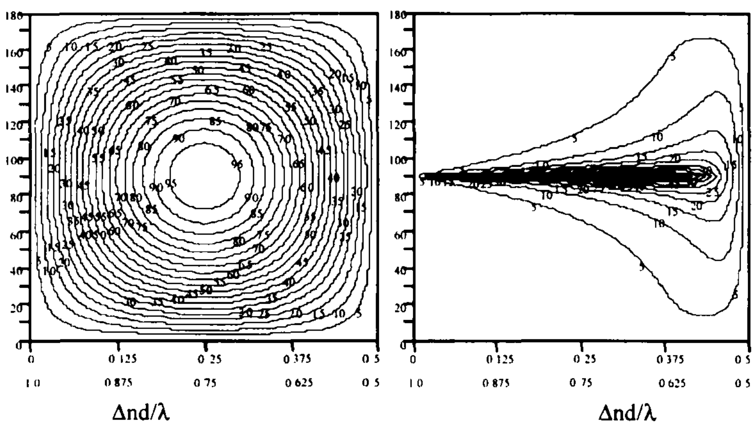

FIGURE 5. Signal-to-noise ratio as a function of the switching angle (vertical axis) and retardation of the cell (horizontal axis) for 2 values of ellipticity: e = 1 (left) and e = 0.86 (right).

CONCLUSIONS

In the case of circular polarization output from the Zeeman laser the alternating signal at the photodetector of the stabilization system is determined solely by the difference of the intensities of the light waves with opposite polarization. The position of the zero point (when intensities are equal) does not depend on the uncertainty of the FLC layer thickness, nor on the switching angle of the FLC material, neither on the symmetry of this switching. All these uncertainties lead only to the decrease of the amplitude of the alternating signal at the photodetector.

The fact that in the process of laser operation the outgoing polarization may become elliptic leads to stronger restrictions on the liquid crystal parameters. The stabilization system is insensitive to ellipticity only in the case when FLC cell has a switching angle of 90° and the cell retardation is close to λ/4. Even a small deviation of the switching angle from 90 considerably changes the optimum values of the LC cell thickness. The FLC mixture CS2005 should provide good discrimination of the light of different polarization and reliable operation of the whole stabilization system. The optimum value of the phase retardation for this mixture is 0.35-0.38 λ.

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