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RING FIBER LASERS FOR TELECOMMUNICATION SYSTEMS

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The goal of this research is to study the interactions between a laser radiation and a liquid-crystal cell and to ensure the mode-locking in a ring fiber laser. In this paper we discuss how a non-linear polarization rotation in ring fiber lasers can be used to achieve the mode-locking. By supplying voltage to a liquid-crystal cell, we studied the polarization behavior both in theory and through experiment. Optical circuit of the ring fiber laser has been suggested.

KEY WORDS: *mode-locking, polarization, stability, radiation intensity*

1. INTRODUCTION

One of the intensively developing areas in telecommunication engineering is new stable sources able to generate at wavelengths belonging to the third fiber optic transmission window. Such devices are ring fiber lasers with passive mode-locking. The erbium-doped optic fiber has been in use as a lasering, operating at $\lambda = 1550$ nm. In future, such lasers may take over the majority of semiconductor data transmission lasers used according to the frequency grid suggested by ITU [1] for DWDM applications.

The recent years is characterized by a tremendous increase in the ring fiber laser engineering. However, the data transmission technology calls for reliable, compact and affordable sources that can compete against the diversity of laser diodes. The available ring fiber lasers, though having their advantages, are not free from drawbacks, among them complicated design [2] and expensive semiconductor saturable absorbers [3]; moreover, such lasers cannot provide a stable operation and have a pulse duration of about 200 fs. Some other designs of ring fiber lasers where mode-locking is ensured by means of the non-linear polarization rotation (NPR) are less expensive to manufacture and provide a pulse duration of about 30 fs [4]. These lasers still have one limitation as for their operating stability and mode-locking. Therefore, we set an objective of developing a ring fiber laser circuit and investigating the ways of mode-locking with the aid of liquid-crystal (LC) polarizers.

2. NRP-BASED MODE-LOCKING

Non-linear polarization rotation (NPR) relies on the relation between the electromagnetic wave polarization status and the strength of radiation at the time of interacting with the substance. If combined with the polarizing beam splitter (PBS), the non-linear polarization rotation acts as a saturable absorber, where the dependence between smaller optic loss in a cavity and increased radiation strength is used to stimulate the output laser pulse generation [5].
In order to achieve this effect, we need a tool to control the polarization in a non-linear medium (i.e., a ring cavity with a discrete component laser). These tools are polarizers (wave plates), rotating in space and, in such a way, ensuring the necessary polarization state (Fig. 1).

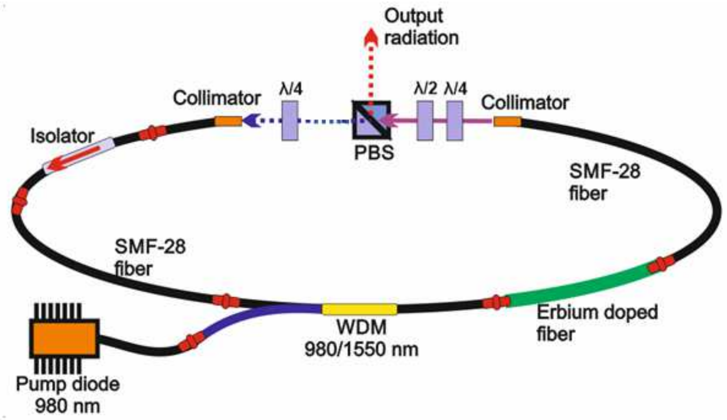

FIG. 1: Circuit of a laser with wave-plate controlled NPR

The authors of [6] have suggested extremely precise motorized polarization rotators. An alternative way implies a mechanical impact on the fiber (bending) to achieve a birefringence [7]. Though the suggested methods require long time to lock modes and tune the laser, the mechanical impact on the optical fiber with e.g., a piezoelectric actuator may be beneficial for a rapid tune-up of the laser, but the force required to ensure the necessary polarization can shift with time, thus calling for additional actions to be taken to properly tune the mode.

The NRP principle optimally suits the fiber lasers, where the distribution of radiation in the optical system allows accumulating the non-linear phase. The temperature, mechanical stress and other factors also contribute to the lasers performance. It provides for a months-long operation of NRP-based fiber lasers without manual tuning, however with a substantial drift, which results in a quenching of lasing.

In this paper, we suggest to use liquid crystals (LC) as polarizers, which are responsible for electronic control of the NRP mode. LC polarizers require control signals of a low voltage, have short response times and a good stability over time. In a where $\alpha 1, \alpha 2$ are rotation angles of the quarter-wave plates, and θ is the rotation angle of the half-wave plate.

Value of $\Delta\phi$ depends on the electric field strength of the light wave, thus, the transmittance of the polarizers is a function of radiation strength. The angles $\alpha 1, \alpha 2$ and θ can be chosen so that the optical components (wave plates) provide the peak radiation transmittance, like a saturable absorber, but with NRP method in place. Figure 3 shows the strength of radiation transmitted by the set of polarizing components as a function of the wave plate rotation angles in space.

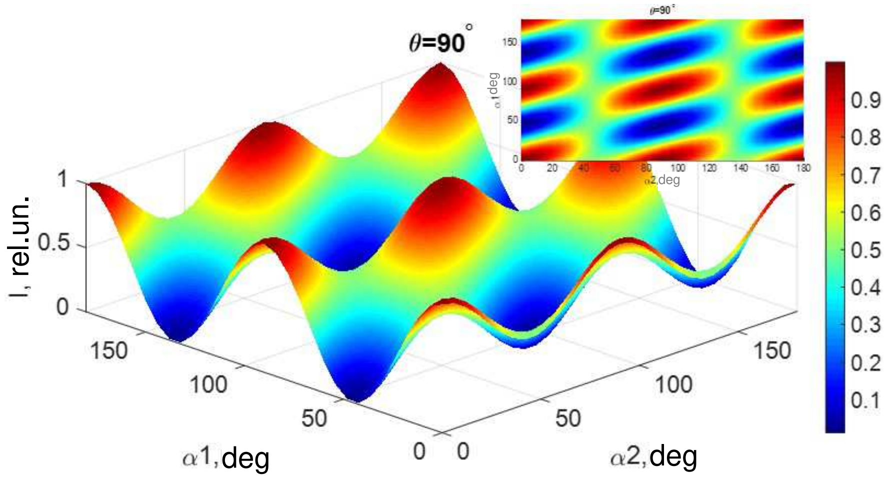

FIG. 3: Dependence between the radiation strength and quarter-wave plate rotation angles ($\alpha 1, \alpha 2$) with the half-wave plate rotation angle being $\theta = 90^\circ$

Thus, when proper rotation angles of the quarter-wave plates in space are chosen and fixed (Fig. 3), it suffices to rotate the half-wave plate alone for NRP to take effect. All drawbacks of the circuit mentioned above can be eliminated by substituting the half-wave plate with a voltage-controlled LC cell.

The Oseen-Frank equation has been applied to study the theoretical aspect of the dependence between polarization and LC cell state:

$$F = \int \left\{ \frac{1}{2} K_{22} \left(\frac{d\theta}{dz} \right)^2 - \frac{1}{2} \varepsilon_0 \Delta\varepsilon E^2 \sin^2(\theta) \right\}, \tag{2}$$

where K_{22} is the elasticity constant, $\Delta\varepsilon$ is the dielectric anisotropy, $\theta(z)$ is the tilt of crystal's director with respect to axis z, and E is the electric field. The equilibrium value of function $\theta(z)$ is chosen so to minimize functional F. While adopting first-order variations, we find that $\theta(z)$ should satisfy the following differential equation:

$$K_{22}\frac{d^2\theta}{dz^2}+\varepsilon_0\Delta\varepsilon E^2\sin(\theta)\cos(\theta)=0. \tag{3}$$

Expression (3) is a second-order differential equation. In order to solve (3) numerically, it should be linearized by introducing substitutions $\theta(z)\to\theta_1$ and $\theta'(z)\to\theta_2$.

The reorientation of liquid crystal affects the electric field as a result of the permittivity change. In such case we need the Laplace equation to find its value:

$$\nabla\varepsilon\nabla u=0, \tag{4}$$

where u is a potential of the voltage applied to the liquid crystal, and $E=-\nabla u$. Since we deal with a one-dimensional problem only, the Eq. (4) is reduced as follows:

$$\frac{d}{dz}\left[\varepsilon_{zz}\frac{du}{dz}\right]=0, \tag{5}$$

where $\varepsilon_{zz}=\varepsilon_{\perp}+\Delta\varepsilon\sin^2(\theta)$. Then, according to the differentiation rule, we have:

$$2\Delta\varepsilon\sin(\theta)\cos(\theta)\frac{d\theta}{dz}\frac{du}{dz}+\left[\varepsilon_{\perp}+\Delta\varepsilon\sin^2(\theta)\right]\frac{d^2u}{dz^2}=0. \tag{6}$$

Equqtion (6) is also a second-order equation subject to linearization by introducing substitutions $u(z)\to u_1$ and $u'(z)\to u_2$.

As a result, we obtain a set of linearized Eqs. (4) and (6):

$$\begin{cases}\theta_1'=\theta_2,\\ K_{22}\theta_2'+\varepsilon_0\Delta\varepsilon E^2\sin(\theta_1)\cos(\theta_1)=0,\\ u_1'=u_2,\\ 2\Delta\varepsilon\sin(\theta_1)\cos(\theta_1)\theta_2u_2+\left[\varepsilon_{\perp}+\Delta\varepsilon\sin^2(\theta)\right]\cdot u_2'=0.\end{cases} \tag{7}$$

Set (7) includes four linear differential equations and is solved by finding $\left\{\theta_1',\theta_2',u_1',u_2'\right\}$.

The described mathematical model allows, by means of mathematical and numerical techniques, to analyze electrooptical parameters of liquid crystals and use this knowledge to efficiently implement them as polarization controllers in ring fiber lasers. Curves in Fig. 4 present the dependence between polarization rotation angle and the voltage applied to an LC cell, estimated in theory and experiment.

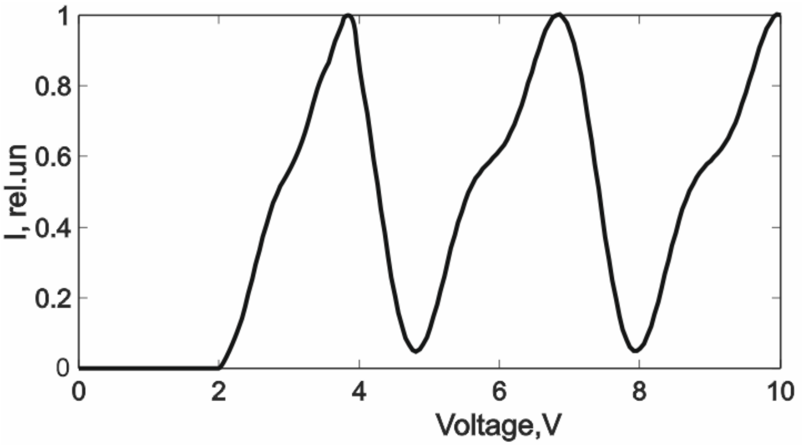

FIG. 5: Dependence between strength of radiation transmitted through the optical system and voltage applied to the LC cell

4. CONCLUSIONS

In this study we analyzed some aspects of radiation transmission through wave plates and PBS, which allowed us to calculate in theory the stability parameters for a fiber laser without LC cells. Equation (1) was obtained after the matrix technique (the Jones polarization rotation matrix). We demonstrated in theory and practice how to control polarization with an LC cell (Fig. 4), while the experimental and theoretical data showed a good agreement. Theoretical research proved the operation stability of a laser equipped with a voltage-driven LC polarizer (Fig. 5). The laser in Fig. 2 is free from drawbacks inherent in its analogues, while offering such advantages as simple mode tuning by changing the voltage applied to LC cells, stable long-term operation and relatively moderate cost of the device. During this study we implemented a new mode-locking technique based on the non-linear polarization rotation in ring fiber lasers. The suggested circuit of the ring fiber laser can entirely replace lasers and semiconductor sources used for data transmission according to ITU recommendations as for the frequency grid in DWDM applications.

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