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Model and Simulation of a Tunable Birefringent Fiber Using Capillaries Filled with Liquid Ethanol

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Abstract: Conventional polarization maintaining fiber is constructed using a pair of borosilicate rods on either side of the fiber core. Current manufacturing processes prohibit the construction of fibers with the required accuracy needed for applications requiring precision birefringence. This paper describes simulated results of fiber with a mutually orthogonal secondary set of capillary tubes filled with liquid ethanol. The results show that it is possible to "tune" the birefringence in these fibers over a limited range depending on the temperature at which the ethanol is loaded into the capillaries. Over this tuning range the thermal sensitivity of the birefringence is an order-of-magnitude lower than conventional fibers, making this technique well suited for applications requiring precision, thermally insensitive birefringence in optical fibers.

Keywords: birefringence, tunable, fiber, isolator

1. Introduction

Optical isolators play a critical role in the fabrication of high power fiber amplifiers. Their purpose is to protect optical sources from light traveling in the backward direction, which can cause damage to the optical source and/or components downstream. The major sources of backward traveling light in high power fiber lasers and amplifiers are reflections from the fiber output facet, spontaneous Raleigh scattering (SRS), stimulated Brillouin scattering (SBS), and amplified spontaneous emission (ASE). It is often necessary to incorporate isolators capable of suppressing backward power of at least 1–5% of the output power of the laser or amplifier. Current (free space) isolators can handle average powers up to the order of 100W with limited beam distortions. For fiber-coupled devices, the power levels are currently limited to about 50W. Recent demonstrations show continuous wave (CW) diffraction-limited power in fiber amplifiers scalable to the kW level [1]. These amplifiers are often seeded with powers approaching the current tolerances of fiber-coupled isolators to avoid ASE inside the amplifier. Therefore, fiber coupled isolators are prohibited for these types of systems [2]. It is possible to employ high-power free-space isolators to avoid these power limitations, however, these isolators tend to be lossy, require precision alignment, and prohibit an all-fiber, monolithic system. Overcoming the power limitations associated with fiber-coupled isolators at the 100W level is a tremendous challenge and creates a demand for novel concepts in optical isolation. One such concept uses a polarization-maintaining (PM) fiber with a secondary set of orthogonal capillary tubes filled with liquid ethanol [2]. This fiber is used in conjunction with a polarization rotating technique known as magnetic quasi-phase matching, where the polarization beat length at the wavelength of the fiber amplifier is matched to the period of an array of permanent magnets [3].

2. Magnetic Quasi-Phase Matching

By matching the beat length of a birefringent fiber to the period of a spatially alternating magnetic field 45° Faraday rotation of the polarization vector is achievable in undoped silica fiber in less than 1m. This configuration is shown in Figure 1. The fiber(s) are placed between two rows of magnets arranged with alternating polarities. In this configuration, the polarization beat length L at the wavelength of light propagating in the fiber core is chosen to closely match the period $2l$ of the magnetic array. When a pair of crossed polarizers is placed on the front and backsides the transmission in the forward and reverse directions is:

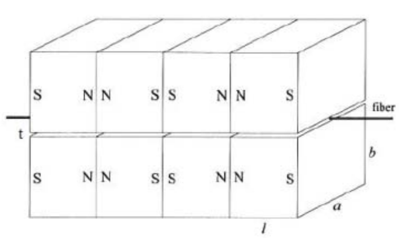

Figure 1. Example of quasi-phase matching technique.

$$T_{fwd} = \frac{1}{2}\left(1 + \sqrt{1 - \Delta^2}\right) \qquad (1)$$
$$T_{bwd} = \frac{1}{2}\left(1 - \sqrt{1 - \Delta^2}\right)$$

where,

$$\Delta \equiv \left|E_x\right|^2 - \left|E_y\right|^2 = 1 - 2\left(V\overline{B}/\beta\right)^2 \sin^2 \beta z, \qquad (3)$$

describes the difference between the x and y field intensities. In the above equations V and $\overline{B}$ denote the Verdet constant of the fiber and the phase-matched Fourier component of the spatially oscillating magnetic field. β is a function of a "detuning" parameter q:

$$\beta = \sqrt{q^2 + \left(V\overline{B}\right)^2}, \qquad (4)$$

$$q = \pi\left(1/2l - 1/L\right). \qquad (5)$$

The beat length L is equal to the wavelength λ divided by the fiber birefringence B:

$$L = \lambda / B. \qquad (6)$$

With a magnetic field of about 0.75 Tesla, sufficient Faraday rotation at 1 µm wavelength requires a magnet array about 1 m long.

3. Tunable Birefringence using Pressurized Liquid Capillaries

As shown in Eq. (6) the beat length of the fiber may be controlled by varying the birefringence B. Typically fibers are manufactured with a set birefringence through the use borosilicate rods inserted in the fiber perform as shown in Figure 2. The magnitude of the birefringence is determined by several parameters. Referencing Figure 4, d_1 and r_1 describe the distance between the stress applying parts and the size of the stress rods respectfully. a and R denote the fiber core and fiber size respectively. The relationships between stress, strain, and thermal expansion are given by: [4]

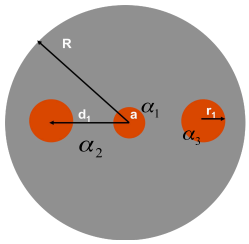

Figure 2. Example of standard (PANDA) fiber.

$$\begin{aligned}
\varepsilon_x &= \frac{1}{E}\left[\sigma_x - v\left(\sigma_y + \sigma_z\right)\right] + \alpha\Delta T, \\
\gamma_{xy} &= \frac{\partial u}{\partial y} + \frac{\partial v}{\partial x}, \\
\varepsilon_y &= \frac{1}{E}\left[\sigma_y - v\left(\sigma_x + \sigma_z\right)\right] + \alpha\Delta T, \\
\gamma_{xz} &= \frac{\partial u}{\partial z} + \frac{\partial w}{\partial x}, \\
\varepsilon_z &= \frac{1}{E}\left[\sigma_z - v\left(\sigma_x + \sigma_y\right)\right] + \alpha\Delta T, \\
\gamma_{yz} &= \frac{\partial v}{\partial z} + \frac{\partial w}{\partial y},
\end{aligned} \tag{7}$$

where $\varepsilon_x \ldots \gamma_{yz}$, are called the components of strain. E, α, and ΔT denote Young's Modulus, thermal expansion coefficient, and the change in temperature between the fiber draw temperature and operating temperature respectively. σ_x, σ_y denote the stress in the x and y directions respectfully. In general the strain in each principal direction is related to the respective displacements u,v,and w as:

$$\begin{aligned}
\varepsilon_x &= \partial u / \partial x \\
\varepsilon_y &= \partial v / \partial y . \\
\varepsilon_z &= \partial w / \partial z
\end{aligned} \tag{8}$$

The birefringence in the fiber depends on the relative difference between the stresses in the x and y directions and C the stress-optic coefficient:

$$B = C\left(\sigma_X - \sigma_Y\right). \tag{9}$$

Birefringence is created due to the difference in thermal expansion between the stress rods, core, and the surrounding cladding as shown in Figure 2. In this way, the birefringence of the fiber is set when the fiber is drawn and varies slightly at different operating temperatures. The thermal variation is problematic since the Magnetic Quasi phase matching technique described in Section 2 is sensitive to changes in the birefringence. A solution to the problem is to construct a fiber using a secondary; mutually orthogonal set of liquid Ethanol filled capillary tubes as shown in Figure 3. In this way, the birefringence can be "tuned" using the loading pressure of the Ethanol while at the same time providing a more thermally insensitive device.

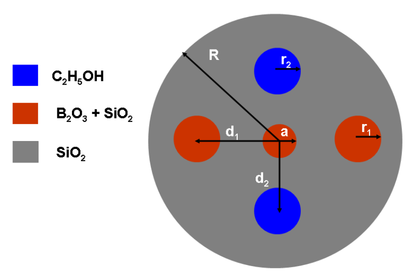

Figure 3. Conventional fiber with a secondary set of mutually orthogonal capillary tubes filled with liquid ethanol.

In the case of a standard fiber shown in Figure 2 equations 7, 8, and 9, may be solved with analytic methods by forcing continuity across the interfaces and making the radial stress go to zero a the fiber boundary. With the addition of the pressure introduced in the walls of the liquid filled stress rods the boundary conditions across the interface between the capillary walls and the surrounding cladding is such that the pressure is continuous:

$$\sigma_{r=boundary} = P(\rho,T), \qquad (10)$$

where $P(\rho,T)$ denotes the pressure on the walls as a function of density and temperature of the liquid ethanol. The pressure on the boundary of the holes is determined using the empirical equation-of-state of liquid Ethanol [5,6]:

$$p - p_o = \sum_{i=1}^{3}\sum_{j=0}^{3} C_{ij}\left(\rho - \rho_o\right)^i T^j$$
$$\rho = \rho_o / \left[1 - \sum_{i=1}^{3} A_i T^i Ln\left(1 + p\sum_{j=1}^{3} B_i T^j\right)\right], \qquad (11)$$

and,

$$\rho_o = 806.594 - 0.84589 T_{load} - 1.361x10^{-4} T_{load}^2 - 5.557x10^{-6} T_{load}^3, \qquad (12)$$

where p, p_o, ρ, p_a and T, T_{load} denote pressure, reference pressure, density, reference density, operating temperature, and loading temperature respectfully. In this configuration the symmetry of the problem is broken, and an analytic approach is unknown to these authors. For this reason, we approach this problem using the Finite Element Method (FEM).

3. Use of COMSOL Multiphysics

Using Comsol equations (7)-(12) were solved numerically in the plane-strain approximation on a triangular mesh with 13112 elements and 6651 mesh points. The geometry was constructed inside the Comsol IDE using the heat transfer module in conjunction with the Structural Mechanics, Plain Strain application mode. A sub-domain expression was constructed to compute the average birefringence across the core in accordance with Eq. (9). We exported a Matlab script in order to interface with Matlab .m files that solved for the pressure on the surface walls using Eqs. (11)-(12). This information was passed into the Comsol script file to specify the boundary condition of the radial stress on the inner surface of the capillary tubes. The stress and the displacement at the fiber boundary were set to zero. In general, the average birefringence of the core as well as the sensitivity of the birefringence to temperature is dependent on the several factors mentioned in the preceding section. Referencing Figure 3 in the fiber with the secondary set of liquid rods, two additional factors are introduced: d_2, the distance from the center of the fiber to the liquid rod center, and the loading temperature T_{load}, of the liquid Ethanol. We found the Comsol-Matlab script interface particularly useful in this regard since it gives us the interface capability to study a variety of different parameter spaces.

4. Results

In an effort to limit the parameter space we fix the core and cladding diameter to 25μm and 200μm respectfully. Furthermore, we restrict the loading temperature of the liquid ethanol to a span -80ºC to 40ºC and assume a draw temperature of 1073ºC. We then generated a large sample space for the parameters r_1, r_2, d_1, d_2, and T_{load}. For each set the average birefringence and sensitivity of the birefringence with respect to temperature was computed over the fiber core. The objective was to find parameters such that $(1/B)\partial B/\partial T$ was as small as possible (insensitive to temperature effects over the loading temperature range) while at the same time offering a large tune- ability in the beat length with respect to the loading temperature of the Ethanol $\partial Beat/\partial T_{load}$. A further restriction was to limit the beat length at $\lambda = 1.064\,\mu m$ to approximately 1.7cm near room temperature. The relevant parameters and constants used in the following simulations are given in table 1.

Name	Expression	Description
R	0.0001[m]	Fiber Radius
T_{melt}	1346.15[K]	Fiber Melting Temperature
E	73e9[Pa]	Young's Modulus of Fiber
α_{solid}	2.28e-006[1/K]	Thermal Expansion Coefficient of solid rods
α_{clad}	5e-007[1/K]	Thermal Expansion Coefficient of Cladding
ν	0.17[1]	Poison's Ratio of Fiber
a	1.25e-005[m]	Core Radius
C	3.22e-012[1/Pa]	Stress-Optic Coefficient at 1064nm

Table.1. Simulation Parameters

The "tune ability" of the birefringence is dictated by the pressure exerted by the liquid Ethanol on the walls of the capillary tubes. In this model the liquid-filled capillaries are assumed to be loaded at atmospheric pressure and a loading temperature spanning -80ºC to 40ºC. The capillaries are assumed sealed after loading such that the density remains constant and is given by Eq. (12). A plot of the pressure on the boundary of the liquid-filled holes vs. operating temperature is shown in Figure 4. The radial pressures considered here span a range of 0 – 200 MPa and are well within the Bulk Modulus of fused silica ~ 30GPa. Near room temperature the wall pressure can be "tuned" from approximately 30-160 MPa, resulting in a range of stresses applied in the orthogonal directions relative to the standard borosilicate rods. After considering a significant portion of the parameter space, the fiber parameters listed in Table 2 contained the largest potential for tunability, while at the same time maintaining temperature insensitivity near room temperature.

Figure 5 shows a plot of the birefringence resulting from stress contributions from both the solid and liquid filled rods with the parameters shown in Table 3. Notice the strong contribution of stress from the solid rods relative to the stress induced from the pressure on the capillary walls. In this way the liquid filled Ethanol provides precise tunability based on the loading temperature.

Another important feature of Figure 5 is that the birefringence is uniform over the central core region, an important design consideration for a birefringent fiber. Figures 6 and 7 show plots of the average core birefringence and the sensitivity of the birefringence with respect to different operating temperatures. Notice that in the normal operating regime (20-40 ºC) the susceptibility of temperature induced changes in birefringence is minimal $(1/B)\partial B/\partial T \sim 10^{-5}K^{-1}$ for loading temperatures spanning (-65 … -35) ºC.

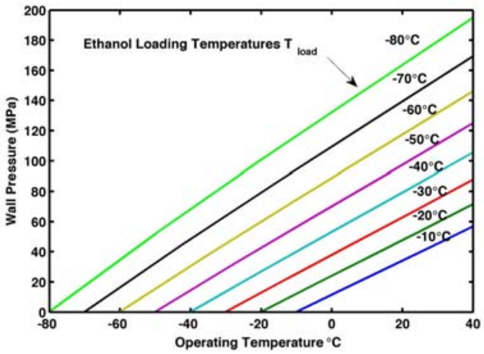

Figure 4. Wall Pressure vs. operating temperature of capillary tubes filled with liquid ethanol

Name	Expression	Description
R	0.0001[m]	Fiber Radius
d_1	3.46e-005[m]	Center-to-center distance of solid rods
d_2	4.78e-005[m]	Center-to-center distance of solid rods
r_1	8.2e-006[m]	Solid rod radius
r_2	2.9e-006[m]	Liquid rod radius
a	1.25e-005[m]	Core Radius

Table.2. Optimal parameters determined from parametric study of the parameter space.

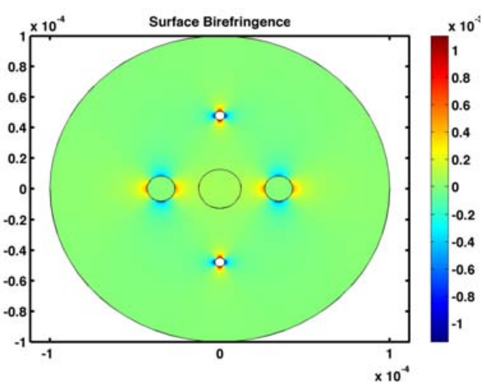

Figure 5. Example of birefringence of a fiber with both liquid and solid stress rods. The liquid capillary tubes and solid stress rods are shown aligned with the vertical and horizontal axes respectfully.

This is nearly an order of magnitude smaller than that of most standard fibers 5-7 x$10^{-4}K^{-1}$.

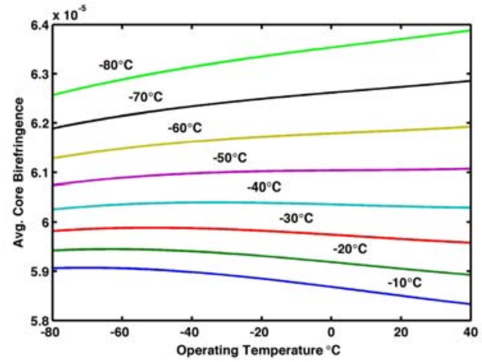

Figure 6. Avg. Core Birefringence vs. Operating Temperatures

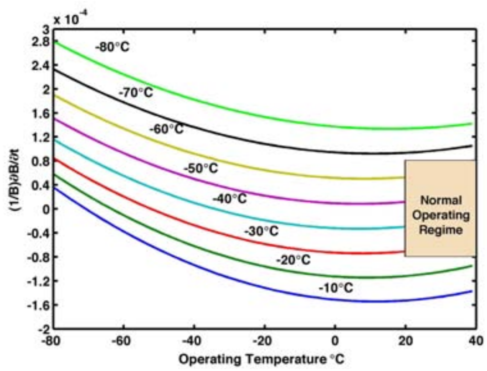

Figure 7. Normalized change in birefringence with respect totemperature vs. operating temperature.

Figure 8 shows the corresponding beat length for this fiber using a wavelength of $\lambda = 1.064\,\mu m$. Notice that over the

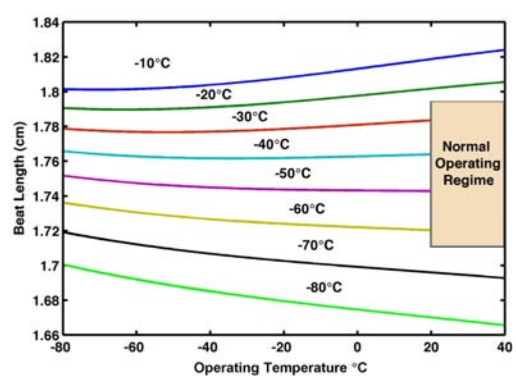

Figure 8. Beat length vs. operating temperature for various Ethanol loading temperatures.

same operating regime (20-40 ºC) the beat length may be "tuned" from (1.68 - 1.82) cm; or approximately 2 mm, close to the 2mm required to have an isolator tunable over 20nm.

4. Conclusion

A tunable, temperature insensitive, birefringent fiber was theoretically designed by investigating the use of a secondary set of mutually orthogonal liquid-filled capillaries in conjunction with traditional borosilicate stress rods. Although this work is concerned with using this technique to construct a fiber with a nominal beat length of 1.75cm, a similar analysis could be done aimed at designs spanning a range of beat lengths. This paper has demonstrated that, by using a secondary set of capillaries filled with liquid Ethanol, two of the practical limitations facing an all-fiber isolator using magnetic quasi-phase matching can be overcome: tunability is enabled to a selected wavelength within a range of ~ 20nm and temperature-insensitive birefringence is obtained.

8. References

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9. Acknowledgements

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