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OPTICAL PHYSICS

Birefringent filters in fiber systems

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Birefringent filters (or Lyot filters, as their implementation is most widely used in lasers) are popular radiation wavelength selectors. Their adaptations to fiber lasers are quite diverse and feature many original solutions. This work analyzes various configurations of Lyot filters in fiber lasers and discusses modifications of these filters under new conditions. The question is further discussed regarding the possibility of choosing the initial birefringence value in the discrete and fiber-optical implementations of the filter, and of subsequent birefringence adjustment. Also, the prospects of electronically controlled Lyot filters and their application in fiber-optical sensors are explored. Peculiarities of all-fiber Lyot filters are demonstrated in comparison to their conventional implementations.

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1. INTRODUCTION

Birefringent (BF) filters are a common type of radiation wavelength selector in volumetric tunable lasers (VTLs) [1–3]. This type of selector is long and well-known [4–7], and it consists of sequentially placed BF plates made of the same material and polarization analyzers. As the light passes through a BF plate, its initial polarization (usually linear) generally undergoes a change (the output polarization depends on the thickness of the plate, index of BF, and radiation wavelength). The light then passes through the polarization analyzer. This function may be performed by polarizing materials, Brewster plates (partial polarizers), and other optical elements that may have different transmittances for radiation with different polarizations. The radiation with changed polarization suffers losses, whereas that with unchanged polarization has the highest transmittance. The transmission function of a BF filter composed of a BF plate sandwiched between two polarizing analyzers exhibits a series of transmission peaks corresponding to the radiation wavelengths that do not change polarization when passing through the filter. A salient feature of BF filters is a relatively large distance ($\gtrsim$ 150 nm) between the transmission peaks at a reasonable thickness of the BFt plate (e.g., 0.3–0.5 mm for a crystalline quartz plate).

There exist two most widespread variations of BF filters: Lyot [4] and Solc [7] filters. In Lyot filters used in lasers, each BF plate is inserted between two polarization analyzers (this role is often played by Brewster surfaces of these plates if positioned with a tilt), whereas in Solc filters, polarization analyzers are only used at the input and output of the entire set of BF plates. Another difference between these types of filters is that Lyot filters use plates of different thicknesses (they differ by a factor of n), whereas in Solc filters, all plates have the same thickness. It is more difficult to ensure low transmission losses in a Solc filter because the plate faces need an anti-reflection coating. This is why Lyot filters are more often used in lasers.

In order to narrow down the transmission peak of a Lyot filter, additional BF plates of greater thickness are inserted. In such a configuration, the distance between the main transmission peaks (with ∼100% transmission) is determined by the thinnest plate, and the width of the transmission peak is defined by the thickest plate.

This work analyzes the application of BF filters (Lyot filters, mostly) in fiber lasers, discusses various ways of their use, and estimates the prospect of adaptation of this selector type to fiber lasers.

A. Impossibility of Using a BF Selector in Fiber Lasers As It Is Used in Volumetric Tunable Lasers

In VTLs, the selector usually needs to provide a relatively small discrimination of radiation at unwanted wavelengths. This is related to a relatively low-active medium gain. The optimal transmittance of the cavity output coupler is ∼5%−10%, and so the single-pass losses at the unwanted wavelengths of around ($\lesssim$0.1% are sufficient for their suppression. The transmittance of a Brewster surface for *s*-polarized radiation is ∼0.9 (for a crystalline quartz plate), and for arbitrary polarization, the transmittance of such a Brewster quartz surface is varied within the range of ∼0.9−1.0. Such a relatively low discrimination of undesirable wavelengths is insufficient for a fiber laser, in which the cavity gain is significantly higher compared to volumetric solid-state tunable lasers [8]. The output coupler transmittance in a fiber laser may be as high as 96% (Fresnel reflection from the output face of the waveguide) [9,10]. Therefore, Lyot filters in their conventional low-selectivity configuration (with Brewster surfaces of birefringent plates of the filter as partial polarizers) may not be used in fiber lasers.

B. Adaptation of Birefringent Selectors to Fiber Lasers

In fiber lasers, a BF selector must have better polarization discrimination for radiation of various wavelengths, thus leading to the replacement of partial polarizers with complete ones. Such a role may be played in fiber lasers by polarization-maintaining fibers. For compatibility with the "all-fiber" format, volumetric BF plates are replaced with fiber pieces inserted between two polarizers [11] or polarization-maintaining fibers [12]. Polarization selectivity of fiber-optical "polarizers" may be improved by recording 45°-tilted Bragg gratings into the PM fibers, between which the analog of the birefringent Lyot filter plate is spliced [13]. The fiber pieces playing the role of BF plates may be made of the standard SMF fiber [14] or polarization-maintaining fiber, whose axis is rotated (usually by 45°) with respect to the axes of the input and output fiber polarizers [15,16]. The fiber stretches, playing the role of BF plates, as a rule, have fixed birefringence, even though it was already demonstrated that it is possible to adjust it dynamically through mechanical [14,17] or thermal [17–19] action on the fiber. Mechanical action on an optical fiber aimed at modifying birefringence may be implemented by both variation of applied tension and bending of the fiber wound around a reel with an adjustable diameter [14]. Modification of birefringence caused by change in the fiber bend radius was discovered relatively long ago [20–22]. This effect allows making a Lyot filter "plate" with adjustable birefringence out of standard single-mode fiber wound around a reel with an adjustable diameter [23]. It is also possible to modify the fiber birefringence through a fiber-optical polarization controller directly acting on the Lyot filter fiber [24].

In a BF filter, the role of optical plates with different thicknesses (and therefore with different selectivity values) may be played by pieces of fiber with varying lengths, and synchronous detuning of their transmission peaks may be achieved by making them out of the same material and changing their temperature synchronously. Rather infrequently, spectral tuning is achieved by imitation of rotation of the fiber-optical version of the BF selector "plate" [25] (rather than the PM fiber itself, the plane of radiation polarization is rotated around the PM fiber by two half-wave plates inserted at the input/output of the fiber). This is similar to the rotation of the BF plate of the selector in its free-space volumetric implementation but violates the "all-fiber" concept.

Generally, the wavelength tuning of a fiber-based BF selector is its weak spot. Until now, there is still no generally accepted, fast, and convenient (let alone electronically driven) tuning method. We will mention only one approach that allows manual control of spectral tuning of a BF filter. It consists in splicing into the filter fiber a polarization controller, which allows manual adjustment of the total birefringence of a filter "plate" [26]. The adjustment of the degree of birefringence is possible not only with the help of a polarization controller but also with a variable wave retarder placed next to the stationary birefringent fiber [27]. The birefringent fiber sets a basic delay in the propagation of orthogonally polarized waves, and the additional element (the radiation polarization controller or variable wave retarder) can modify this delay.

It should be noted that the wavelength tuning function of a BF filter is not always required. In many cases, such a filter is used solely for the selection of a specific (or even arbitrary) radiation wavelength. In this case, different plates (or different pieces of fiber) of the BF filter may be made of different materials, and the only necessary condition for the normal operation of such a BF filter as a multi-component selector will be the co-incidence of spectral transmission peaks of all the filter components (plates of fiber stretches). For simplicity of such co-incidence, the filter components are usually made of the same material, but their thicknesses (in the case of plates) or length (in the case of optical fiber) are chosen to be multiples of each other. For a fixed single wavelength, the BF filter does not need any control and may be used as a passive element.

However, Lyot filters may be used not only for the selection of a single wavelength but also for the generation of dual- or multi-wavelength radiation with equidistant spectral positions of radiation lines. Its main advantage in comparison with similar selectors (Fabry–Perot filter, Mach–Zehnder interferometer, and so on) lies in the fact that it may provide relatively large and stable spectral separation of radiation lines via simple means [28–34]. This is important for dense-wavelength-division multiplexed transmission systems and for optical time-division multiplexing techniques.

The Lyot filter does not always allow the selection of the desired wavelength, especially if it includes a manual polarization controller [35]. Changes in birefringence occurring in the process of tuning this controller may be unpredictable. This is why a Lyot filter with such a controller selects an arbitrary radiation wavelength within the active medium gain contour, and the laser itself is called "switchable" instead of "tunable."

The function of a Lyot filter is not limited by the choice of the radiation wavelength(s). The width of the transmission peak affects the output radiation spectral width and may be used for controlling the duration of the generated pulses in short-pulse fiber lasers [16,26,36,37].

2. LYOT FILTER MODIFICATIONS FOR FIBER-OPTICAL SYSTEMS

The most widely used Lyot filter implementation in fiber lasers is a piece of PM fiber inserted between two polarizers (see Fig. 1). Such polarizers may also be made of PM fiber (in which case their optical axes are rotated by 45° to the axes of the central piece). Modifications of the filter are mainly done in two directions:

1. conceptual modifications, in which new mechanisms and/or effects are introduced into the filter operation; and
2. practical modifications, in which the principle of operation remains the same, but the design is somehow adapted to a specific configuration.

Among the examples of conceptual modifications, one can mention the combinations of a Lyot filter with other selectors (Lyot–Sagnac filter [38–40]) and using the laser's active medium as a filter "plate" [41]. Examples of design modifications of the Lyot filter are frequent and include exchanging the

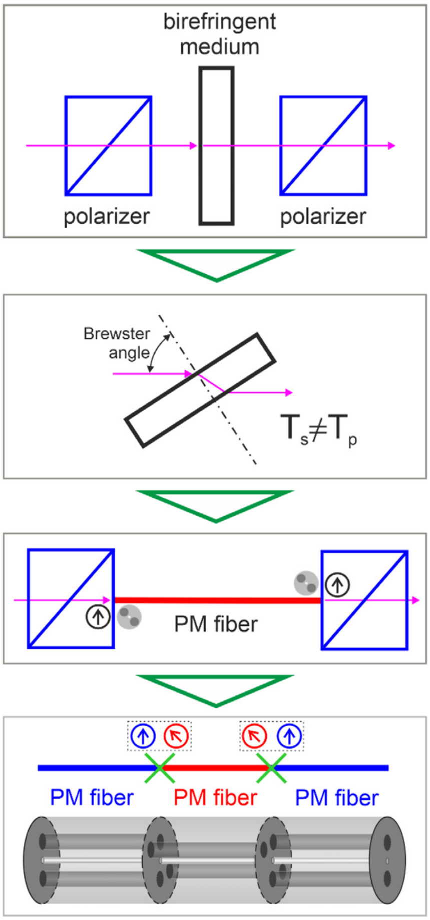

Fig. 1. Evolution of the Lyot filter from discrete to fiber-optical implementation: T, transmission; s, *s* polarization; p, *p* polarization; PM, polarization-maintaining.

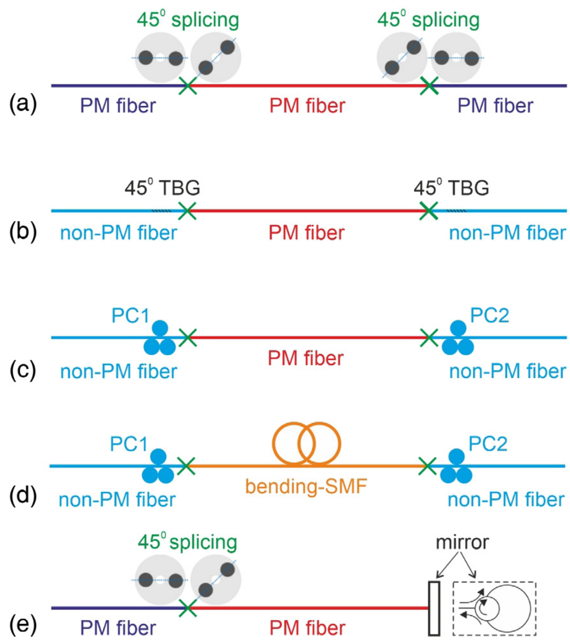

Fig. 2. Examples of implementation of the Lyot filter in ring (a), (b), (c) and linear (d) fiber laser resonators: TBG, tilted Bragg grating; SMF, single-mode fiber.

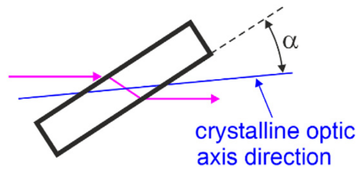

Fig. 3. Illustration of possible choice of optical axis direction in a discrete implementation of a Lyot filter: α, angle between the optical axis and the face of the Lyot filter plate.

standard input or output polarizer for the one making part of an optical diode [42] or for a polarization controller [43], removal of the central piece of the PM fiber, and splicing of the input and output PM fibers at a certain angle [44].

The last example demonstrates that the principle of operation of the Lyot filter may be implemented without a special birefringent optical fiber. Instead, even the standard SMF fiber may be used, where birefringence may arise either due to mechanical stress or to ellipticity of the core. In particular, the traditional radiation polarization controller, in which anisotropic fiber undergoes mechanical action (and becomes birefringent), may play the role of a Lyot filter "plate." Correspondingly, certain implementations [45,46] of wavelength tuning in fiber lasers that rely on changes in polarization do not resemble the Lyot filter externally but are based on its principle of operation and may be considered as artificial Lyot filters. These implementations are most similar to the Lyot filter and not to other polarization filters (Solc filter [7] and Ohman [47]).

It would not be an overstatement to say that in fiber lasers, Lyot filters are used in such modifications that are practically impossible for volumetric lasers with discrete elements.

Let us demonstrate some of the most broadly known fiber-optical modifications of the Lyot filter in ring and linear laser cavities (Fig. 2). Figure 2(a) shows ring cavities made of polarization-maintaining optical fiber, whereas Figs. 2(b) and 2(c) are related to ring cavities mostly made of the non-PM fiber. The function of a radiation polarizer may also be performed by Bragg gratings written into the fiber core at the angle of 45° to the core axis [48–50]. Moreover, Bragg gratings may be imprinted directly into the PM fiber [51]. Figure 2(e) demonstrates a Lyot filter implementation in a linear cavity [52], where the function of reflector may be fulfilled by an ultra-broadband loop mirror based on a fiber circulator [53].

There is another important question that needs to be emphasized when discussing the discrete and fiber-optical implementations of the filter. In the discrete implementation, the initial birefringence value may be selected by choosing the direction of the optical axis (see Fig. 3, angle α). Greater angles α result in higher rates of wavelength tuning (nm/α), and at $\alpha \cong 57°$, this rate reaches its maximum [54]. In a fiber-optical implementation of the filter, the direction of the "plate's" optical axis is determined by the position of the birefringence-inducing stress rods set at fabrication of the PM fiber. Hence, there is practically no possibility of variation of the initial birefringence value through rotation of the optical axis. This is why in fiber-optical implementations of the Lyot filter, the initial birefringence can only be set by choice of the "plate" material.

It is important to mention that the use of birefringent material is not the only way to create a BF filter. Reference [55] proposes a hollow-core fiber that introduces different losses for radiation of different polarizations when bent.

3. ELECTRICAL CONTROL OF LYOT FILTERS

The problem of electrical control over Lyot filters arose a long time ago, and until today, no complete satisfactory solution has been found. In free-space lasers with discrete implementation of Lyot filters, they are usually tuned by the mechanical rotation of the entire filter component. This rotation is performed by a step motor or some other electromechanical drive. Another natural solution is adopting liquid crystals to the role of Lyot filter plates [56]. Electrical control of liquid crystals avoids mechanical movement of the filter for tuning. However, other problems arise related to noticeable optical losses introduced by liquid crystals and their relatively low optical damage threshold. In addition, it is not clear how such a device may be implemented within the “all-fiber” concept. Consequently, this approach cannot be considered optimal. Still another solution relies on an electro-optical crystal (e.g., lithium niobate [57]) as a Lyot filter plate. It is possible to adjust the birefringence of such a plate by the application of high voltage. In fiber lasers, the problem of controlling a Lyot filter is complicated by the continuity of its “plates” with other cavity elements (it is impossible to rotate the “plates” separately) and by the absence of commercial fibers made of electro-optical crystal materials. An electromechanical drive may be used not only for rotation of the Lyot filter but also for mechanical action on the fiber of the fiber-optical implementation of the filter. For example, a piezo-cylinder is used for tensioning the optical fiber wound around it [58].

Dynamic birefringence variation in a Lyot filter “plate” may be achieved by adjustment of a polarization controller placed after the PM fiber (or an SMF bend) within the filter [23,34]. Recently, there started appearing electrically driven fiber-optical polarization controllers [59] that may be used for electronically controlled laser wavelength tuning.

4. FIBER-OPTICAL SENSOR APPLICATIONS OF LYOT FILTERS

The ability of optical fiber to change its birefringence under the influence of external mechanical or thermal factors is utilized for solving problems in sensing. Mechanical factors include tension or compression, shear, torsion, or bending of the fiber. Torsion sensors (in various structures, beams, columns, and so on) are important, and they are used for real-time monitoring of many buildings and structures. Designing such a sensor on the basis of a Lyot filter allows for measurements with interferometric accuracy and highest achievable sensitivity [12,14,60,61]. The sensitivity of Lyot filter “plate(s)” to changes in birefringence, induced by ambient factors and direct physical action on the fiber, makes it possible to use this type of filter as a sensor of various parameters.

It must be pointed out that the sensitivity of birefringence to mechanical pressure on the fiber does not suffer significantly (or even not at all) from a protective sheath of the fiber (either deposited directly onto the cladding or the coating layers). Therefore, fiber-optical sensors based on variation of birefringence are broadly used in construction, for monitoring hydraulic works, as well as railway, electrical power, and oil and gas structures, and so forth. Birefringent sensors are especially sensitive to factors (for instance, pressure) affecting a certain volume of the fiber. In this case, birefringence is more strongly modified. Applications of birefringent fiber-optical sensors do not, as a rule, rely on point detection of any parameters (such as temperature). This type of sensor is effective for the measurement of average values over a certain volume.

5. CONCLUSION

Birefringent filters (usually, Lyot filters) have passed from discrete implementations in volumetric free-space lasers to fiber-optical design in fiber-based systems, where they are used as selectors and sensors. When used as radiation wavelength selectors in fiber lasers, these filters lost the possibility of choosing the direction of the optical axis of the birefringent “plates.” In return, however, they gained the full fiber integration. The fiber-optical Lyot filter still remains the coarsest radiation wavelength selector, and the problem of optimal electronic control of its parameters has not yet been solved. As a fiber-optical sensor, the Lyot filter has found a multitude of applications, mostly related to the detection of volumetric (as opposed to point) action on the fiber.

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