An Optical Filter for Underwater Laser Communications

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Abstract: Optical filters for underwater laser communications have been under development for some time. A free space laser communications system operating in the blue-green portion of the electromagnetic spectrum has the potential to transmit at very high data rates between platforms underwater and to those above the water. Operation during the day requires the ability to receive the maximum amount of light from the laser source coming from a range of angles and simultaneously filtering out solar background noise. We have developed a wavelength-tunable, wide field-of-view, narrow passband, large aperture filter. The filter we have developed is based on a Lyot type birefringence interference filter.

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1. Introduction

Advanced optical systems are being developed for a variety of underwater laser communications applications, including undersea imaging and ranging for anti-submarine warfare and mine detection, marine mammal detection, and submarine laser communication for communications at speed and depth. While most wavelengths of light are severely attenuated in seawater, there is a window in the blue-green region of the spectrum where transmission is highest. In any such system which relies on the detection of laser light, an optical filter is crucial to discriminate the desired laser signal from unwanted scattered light from the sun or other sources. Light is attenuated and scattered as it passes through seawater, so an optimal detection system for undersea laser communications must accept light from a wide range of angles and have a large active area to provide high throughput. Another desirable property of the filter is a narrow bandwidth and tunability for transmission at specific laser wavelengths, and high rejection of light at other wavelengths. This will minimize the background light that creates noise on the desired signal, particularly if the filter and laser combination can operate at a Fraunhofer dark-band. The combination of high throughput and high background light rejection produces greater signal-to-noise. In practice this could mean higher data rates, faster detection times, or greater distance from target.

The filter described in this work is based on a birefringent interference filter with the capability of a large aperture, narrow bandwidth, and wide field-of-view. The birefringent interference filter, was invented by Bernard Lyot in 1933 [1] and later independently by Öhman [2] who constructed the first one to be used for solar observations. A comprehensive description can be found in several references [3,4]. The birefringent filter has previously been used in solar physics on ground based telescopes [5,6] and more recently from satellites [7]. Due to the filter's wide field-of-view, narrow band resolution, imaging capability, large aperture, and tunability it has been applied to a large variety of applications [8] including laser tuning [9], laser ranging [10], medical imaging [11], and remote sensing [12]. The birefringent filter is very flexible in design with spectral resolutions ranging from 10's of nanometers to less than .01 nm.

2. Principle of Operation

The principle of operation of the filter is based on interference of light created by a phase delay in a birefringent crystal. Several variations of the birefringent filter have been demonstrated, with the most common being the Lyot type filter. One of the unique features of the birefringent interference filter is the exceedingly wide field-of-view that can be obtained. A detailed discussion of field-of-view effects and advantages of wide field birefringent filters is given by Title [13].

Several methods have been developed to provide spectral tunability. This is necessary to spectrally align the multiple stages of the filter. It is also necessary for multispectral or hyperspectral systems for tuning over the spectral range of interest or when viewing laser light to tune to the precise wavelength required. Tuning methods can be broadly divided between mechanical and electro-optic techniques. Mechanical rotation requires at least one additional optical element. For the Sacramento Peak Observatory's UBF filter [5] an additional quarter-wave retarder was added to each of nine filter stages. Each polarizer is then independently rotated to adjust the filter wavelength. This adds additional optical elements in each Lyot filter stage and mechanical complexity. Electro-optic techniques have in the past used an additional electro-optic retarder such as ADP/KDP in the filter, as first suggested by Billings [14]. More recently, several birefringent filters have added the tuning capability with the addition of a liquid crystal variable retarder to the fixed retarder [15–17].

3. Design and results

The approach described here is to use a material that can act both as the retarder and the tuning element. This is possible by using lithium niobate, which has a moderately high birefringence and is electro-optically active. The application of an electric field causes the birefringence to change, thus changing the retardation and passband of the filter. This has the advantage of simplifying the overall design and making it more compact, which can be important in applications where a wide field-of-view is desirable. The set of characteristics of a material required for an electro-optically tunable birefringent filter is considerable. An appropriate material must have moderate birefringence, high electro-optic coefficients, large size, high material uniformity, high transmission in the visible, and ease of fabrication. The materials traditionally used in birefringent filters are quartz and calcite. Quartz has a low birefringence ($\Delta n = 0.009$) and therefore requires very thick elements to achieve bandwidths of less then 0.1 nm. It does have the advantage of good availability and ease of fabrication. Calcite has high birefringence ($\Delta n = -0.17$) but uniformity of the material in large size is not readily available. Both of these materials have been used in Lyot filters, and sometimes in combination. They have little or no electro-optic coefficient and therefore require additional elements for tuning. Two crystals that are electro-optically active and available in large size and good optical quality are potassium dihydrogen phosphate (KDP) and lithium niobate (LN). We have chosen to use lithium niobate because of its higher birefringence, ease of polishing, non-hygroscopic properties, availability of high quality lithium niobate wafers with diameters of 100 mm, good transmission, and high electro-optic coefficients.

A number of properties of LN make it very suitable for a birefringent interference filter. Its moderately high birefringence(~ 0.09) allows compact filter designs and high index of refraction (~ 2.24) permits a wider field-of-view since the field-of-view is proportional to $n^{3/2}$, where n is the index of refraction. It has good transmission in the visible and near infrared from $0.4 - 5\ \mu$m. Availability is very good as significant quantities of LN are produced for telecommunication applications. Lithium niobate has previously been used for the birefringent elements in a Lyot filter [10, 18]. In that filter the tuning was accomplished with liquid crystal variable retarders. Lithium niobate has high electro-optic coefficients making it feasible to allow electro-optic tuning. With LN acting as both the birefringent crystal and the tuning element, the filter design is simpler and more compact.

We have designed and tested a Lyot filter utilizing 100 mm LN wafers with a bandwidth of 0.17 nm and a field-of-view of $\pm 18^\circ$. A spectrum of the filter is shown in Fig. 1. A similar filter with a bandwidth of 0.075 nm at 486 nm has also been demonstrated. This new design is operable between 450-550 nm. The tuning capability allows it to be configured for specific laser wavelengths in the blue-green region of the spectrum.

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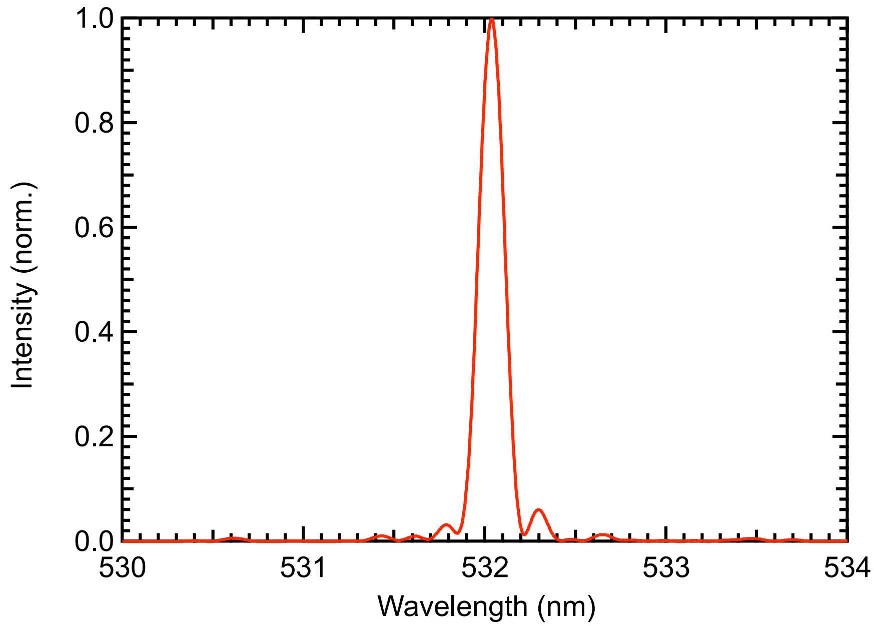

Fig. 1. Measured spectrum of Lyot filter.

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