PARTIAL POLARIZER FILTER

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Abstract

A birefringent filter module comprises, in seriatum, an entrance polarizer, a first birefringent crystal responsive to optical energy exiting the entrance polarizer, a partial polarizer responsive to optical energy exiting the first polarizer, a second birefringent crystal responsive to optical energy exiting the partial polarizer, and an exit polarizer. The first and second birefringent crystals have fast axes disposed ± 45° from the high transmittivity direction of the partial polarizer. Preferably, the second crystal has a length that is 1/3 of the length of the first crystal and the high transmittivity direction of the partial polarizer is nine times as great as the low transmittivity direction. To provide tuning, the polarizations of the energy entering the first crystal and leaving the second crystal are varied by either rotating the entrance and exit polarizers, or by sandwiching the entrance and exit polarizers between pairs of half wave plates that are rotated relative to the polarizers. A plurality of the filter modules may be cascaded. The first crystal for module (n+1) is 2/3 of the length of the second crystal of module n.

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ORIGIN OF THE INVENTION

The invention described herein was made in the performance of work under a NASA contract and is subject to the provisions of Section 355 of the National Aeronautics and Space Act of 1958, Public Law 85-568 (72 Stat. 435; 42 USC 2457), and may be manufactured and used by or for the Government for governmental purposes without the payment of any royalties thereon or therefor.

BACKGROUND OF THE INVENTION

The present invention relates generally to optical, birefringent filters, and more particularly to a birefringent filter including a pair of birefringent crystals of differing lengths, between which is sandwiched a partial polarizer.

One type of prior art birefringent filter module includes similarly aligned, perfect, entrance and exit polarizers, between which is located a birefringent crystal having fast and slow orthogonal axes. The entrance and exit polarizers are rotatable together relative to the birefringent crystal to provide tuning. In response to an optical energy pulse impinging on the entrance polarizer, a pair of output pulses having spaced occurrence times are derived. The spacing between the output pulses is dependent upon the difference in the indices of refraction of the fast and slow axes of the crystal, the length of the crystal, and the speed of light in vacuum. A number of these modules have been cascade together, whereby successive modules include birefringent crystals having lengths related to each other in a geometric progression relative to the length of the module having the longest crystal. Such a birefringent crystal arrangement is frequently referred to as a Lyot filter.

A problem with the prior art Lyot filter is that the amplitude versus output frequency response of the filter includes many secondary maxima of significant amplitude. Thereby, if it is desired for the filter to handle a wide band pass, there is a tendency for significant energy outside of the desired band pass to be passed through the filter, to produce deleterious effects.

SUMMARY OF THE INVENTION

In accordance with a broad aspect of the present invention, a birefringent filter module for optical energy propagating along an optical axis includes entrance and exit polarizers having common polarization directions in a plane at right angles to an optical axis along which the optical energy is propagating. A first birefringent crystal responds to optical energy exiting from the entrance polarizer. The first crystal has a fast and slow axes respectively displaced ±45° from a first polarization direction in a plane normal to the optical axis. A partial polarizer responsive to optical energy exiting the first crystal has orthogonal high and low transmittivity directions in the normal plane, with the high transmittivity direction being in the first direction. A second birefringent crystal responsive to optical energy exiting from the partial polarizer has its fast axis displaced 90° from the fast axis of the first crystal in the normal plane. To minimize secondary maxima, the transmittivity and relative lengths of the two crystals are appropriately selected. In one preferred embodiment, there are minimum secondary maxima by making the first crystal twice as long as the second crystal, and the transmittivity of the partial polarizer is nine times as great in the high transmittivity direction as in the low transmittivity direction.

To tune the crystal, the polarizations of the energy entering the first crystal and leaving the second crystal are rotated. In one embodiment, the entrance and exit polarizers are rotated together about the optical axis relative to the first and second crystals and the partial polarizer. In a second embodiment, two pairs of half wave rotatable plates are provided. The entrance polarizer is sandwiched between one pair of the half wave plates, while the exit polarizer is sandwiched between the other pair of half wave plates. The entrance and exit polarizers are maintained stationary, so they can be easily removed, compared to the ease of removal of the rotatable half wave plates. This is desirable because of the relatively narrow bandwidth properties of birefringent plates relative to half wave plates.

To increase the separation between transmission band passes, a plurality of the filter modules are cascaded along the optical axis. In such a configuration, the first crystal for any downstream module (n + 1) has a length of n of the second crystal for the immediately preceding module, n, and the relative length of the first and second crystals of each of the modules is two to one. In the cascaded configuration, the exit polarizer for module n is the entrance polarizer for module (n + 1).

To enable the device to have a wide effective field of view, each crystal is formed as a Lyot wide field structure including two equal length birefringent segments between which is sandwiched a half wavelength plate. The birefringent crystal segments have fast axes polarized ±45° relative to waves respectively entering and leaving the half wavelength plate and each has a length one half of the total length of the particular crystal.

While it has been analytically shown in the past that partial polarizers between a pair of birefringent equal length filters (having length L) do not have a deleterious effect on Lyot filter performance if the ratio of the polarized to unpolarized light is greater than [(10L² - 1)/L], where n equals the number of intermediate polarizers, it has not been previously realized that advantageous results can be obtained relative to the Lyot filter if the birefringent crystals have differing lengths, with proper selection of the transmittivity of these fast and slow axes. Attempts to build systems employing partial polarizers have not been satisfactory. It is believed that one reason why the prior art attempts have failed is because ordinary partial polarizers are wave plates of differing fractional wavelength that cause rotation of the polarization direction of the incident optical energy. The wavelength of each partial polarizer, and hence the polarization rotation, differs from polarizer to polarizer. In accordance with another aspect of the present invention, the differing wave plate effect of the partial polarizers is overcome by attaching a compensation plate, of known configuration (such as a plastic film), to the partial polarizers so there is no effective polarization rotation by the partial polarizers.

It is, accordingly, an object of the present invention to provide a new and improved birefringent filter.

Another object of the present invention is to provide a birefringent filter having lower secondary maxima in the amplitude versus output frequency response of the filter.

A further object of the invention is to provide a new and improved tunable, relatively wide band optical filter.
Yet another object of the invention is to provide a new and improved optical filter including a plurality of cascaded modules having birefringent filters that are arranged to enable a plurality of different frequency lines within a predetermined band width to be derived.

The above and still further objects, features and advantages of the present invention will become apparent upon consideration of the following detailed description of several specific embodiments thereof, especially when taken in conjunction with the accompanying drawing.

BRIEF DESCRIPTION OF THE DRAWING

FIG. 1 is a perspective diagram of a single module in accordance with the invention;

FIG. 2 is a schematic diagram indicating how a number of the modules are cascaded together; and

FIG. 3 is a schematic diagram of a modified portion of the device illustrated in FIG. 2.

DESCRIPTION OF THE PREFERRED EMBODIMENT

Reference is now made to FIG. 1 of the drawing wherein one preferred embodiment of a birefringent filter module in accordance with the present invention is illustrated. Module 11 of FIG. 1 includes a number of optical elements having entrance and exit faces in planes normal to optical axis 12, along which an optical beam to be filtered is propagated. The beam entering module 11 is plane polarized, and enters the module from the lower left side thereof, as illustrated in FIG. 1. The beam emerges from module 11, as a plane polarized beam, having the same polarization direction as the incident beam, from the end of the module illustrated in the upper right hand corner. A beam entering and leaving module 11 that is polarized in the horizontal direction, as indicated by arrow 13, is considered to be polarized in a first or reference direction.

The elements of module 11 are, from the entrance to the exit, perfect polarizer 14, quarter wave plate 15, a first birefringent crystal 16, partial polarizer 17, a second birefringent crystal 18, quarter wave plate 19, and perfect polarizer 20. While each of the elements 14-20 is illustrated as being square in the planes normal to axis 12, it is to be understood that usually these elements are circular in the planes normal to axis 12; the elements are shown as being square in cross-section to facilitate the description.

To provide tuning, polarizers 14 and 20 are rotatable about axis 12, in planes normal to the axis, whereby the amplitudes of the optical energy respectively incident on an entrance face of quarter wave plate 15 and exiting from module 11 are varied. The remaining elements of module 11 are stationary relative to axis 12. Quarter wave plate 15 changes the linearly polarized light that is incident on it into elliptically polarized light having components that are determined by the relative polarization angles of the optical energy incident on polarizer 14 and the polarization axis or direction of polarizer 14. Conversely, quarter wave plate 19 changes elliptically polarized light that emerges from birefringent crystal 18 into linearly polarized light that is selectively passed through polarizer 20, depending upon the polarization directions of the light emerging from plate 19 and the polarization direction of polarizer 20.

Birefringent crystals 16 and 18, having slow and fast axes that are mutually orthogonal to each other and differing lengths. The lengths of crystals 16 and 18 and the transmittivities of the high and low polarization directions of partial polarizer 17 are selected to provide minimum secondary maxima for the wavelengths emerging from module 11. Crystal 16 has a length that is dependent on the region in the optical spectrum of the optical energy propagating along axis 12, and which is to be filtered by module 11. Fast and slow axes 22 and 23 of crystal 16 are respectively displaced, in the normal plane, by ± 45° from direction 13. In an opposite sense, the slow and fast axes 24 and 25 of crystal 18 are displaced, in the normal plane, ± 45° from direction 13. Partial polarizer 17 is arranged so that it has high and low transmittivity directions in the normal plane, respectively aligned with and orthogonal to direction 13, as indicated by arrows 26 and 27.

In a preferred embodiment, to minimize secondary maxima, crystal 16 has a length, along axis 12, twice the length of crystal 18 and the transmittivity of partial polarizer 17 along axis 26 is nine times as great as the transmittivity of the partial polarizer along axis 27. The effectiveness of the module illustrated in FIG. 1 can be realized by considering the transmittivity response as a function of wavelength relative to the wavelength of crystal 16, if it is assumed that a normalized transmittivity of 1.00 is derived from perfect polarizer 20 when the optical energy incident on quarter wave plate 15 has a wave length that causes crystal 16 to be tuned. A first secondary maximum, having a transmittivity of approximately 0.18% of the transmittivity for the tuned condition, occurs at a wavelength that is approximately 1.4 times the full width at half maximum removed from the tuned wavelength. A second secondary maximum, having an amplitude of approximately 0.394% of the normalized transmittivity occurs for a wavelength that is approximately 3.5 times the full width at half maximum removed from the tuned wavelength, while a third secondary maximum has a transmittivity of approximately 0.08% at a wavelength that is displaced from the tuned wavelength by approximately 5 times the full width at half maximum. At wavelengths removed by more than 5 times the full width at half maximum removed from the tuned wavelength, all secondary maxima are virtually suppressed.

In contrast, if a perfect polarizer is employed between birefringent crystals 16 and 18, the secondary maxima have progressively decreasing amplitudes. The first secondary maximum, displaced from the tuned condition by 1.5 times the full width at half maximum of the tuned frequency, has an amplitude that is 4.3% of the normalized amplitude for the tuned condition. The second secondary maximum, at a wavelength 2.5 times the full width at half maximum removed from the tuned wavelength, has an amplitude of 1.6% of the normalized amplitude. The third secondary maximum, at a wavelength 3.5 times the full width at half maximum removed from the tuned wavelength, has an amplitude of approximately 0.8% of the tuned amplitude; the fourth secondary maximum, at 4.5 times the full width at half maximum wavelength, has an amplitude of approximately 0.5% of the normalized amplitude; and the fifth secondary maximum, at a wavelength of 5.5 times the full width at half maximum of the tuned frequency wavelength, has an amplitude of 0.3% of the normalized amplitude. It is thus apparent that the total secondary energy passing through a first secondary maximum of the present invention is considerably less than in the prior art situation wherein a perfect polarizer is em-
ployed and that better filtering close to the tuned wave-
lengfh is provided.

To enable module 11 to function effectively to achieve the aforementioned results, it is necessary for no effective polarization rotation to be introduced by partial polarizer 17. It has been found, however, that partial polarizers do cause rotation of the polarization direction of optical energy incident thereon. It has also been found that the wavelength of each partial polar-
zcr, and hence the amount of polarization rotation, differs from polarizer to polarizer. To compensate for 
the variable polarization rotation introduced by partial polarizer 17, the polarizer is provided with a compens-
sating plate 28, in the form of a plastic film that is at-
checl to a face of the partial polarizer in the normal 
plane. Film 28 has a thickness to compensate for the 
polarization rotation by partial polarizer 17, whereby the energy exiting the partial polarizer is polarized in 
the same direction as the energy incident on the partial polarizer and there is no effective polarization rotation by the partial polarizer. The thickness of film 28 must be determined separately for each partial polarizer 17.
high transmittivity direction being in the first direction, a second birefringent crystal responsive to optical energy exiting the partial polarizer, said second crystal having a fast axis displaced 90° from the fast axis of the first crystal in the normal plane, and an exit polarizer, said exit polarizer being polarized in the normal plane, the lengths of the first and second crystals differing from each other.

2. The module of claim 1 wherein one of the crystals has a length twice that of the other crystal.

3. The module of claim 1 further including compensating means on the partial polarizer for compensating the tendency of the partial polarizer to rotate the polarization direction of optical energy incident thereon so that optical energy entering and leaving the partial polarizer has the same polarization direction.

4. The module of claim 2 further including compensating means on the partial polarizer for compensating the tendency of the partial polarizer to rotate the polarization direction of optical energy incident thereon so that optical energy entering and leaving the partial polarizer has the same polarization direction.

5. The module of claim 1 wherein the transmittivity of the partial polarizer is 9 times as great in the high transmittivity direction as in the low transmittivity direction.

6. The module of claim 5 wherein one of the crystals has a length twice that of the other crystal.

7. The module of claim 6 further including compensating means on the partial polarizer for compensating the tendency of the partial polarizer to rotate the polarization direction of optical energy incident thereon so that optical energy entering and leaving the partial polarizer has the same polarization direction.

8. The module of claim 1 further including means for rotating the polarizations of the energy entering the first crystal and leaving the second crystal relative to the crystals and the partial polarizers.

9. The module of claim 8 wherein the means for rotating includes means for rotating the entrance and exit polarizers relative to the first and second crystals and the partial polarizer.

10. The module of claim 9 further including compensating means on the partial polarizer for compensating the tendency of the partial polarizer to rotate the polarization direction of optical energy incident thereon so that optical energy entering and leaving the partial polarizer has the same polarization direction.

11. The module of claim 8 wherein the means for rotating includes a first pair of \( \frac{1}{2} \) wave plates between which said entrance polarizer is sandwiched, and a second pair of \( \frac{1}{2} \) wave plates between which said exit polarizer is sandwiched, and means for rotating said first and second pairs of \( \frac{1}{2} \) wave plates relative to each of the entrance and exit polarizers, the first and second crystals and the partial polarizer.

12. The module of claim 1 wherein a plurality of the filter modules defined in claim 1 are cascaded along the optical axis, the relative lengths of the first and second crystals of each of said modules being 2:1, the exit polarizer for module \( n \) being the entrance polarizer for module \( (n+1) \), the first crystal for module \( (n+1) \) having a length of \( \frac{1}{2} \) of the second crystal for module \( n \).

13. The module of claim 12 wherein the transmittivity of each partial polarizer is 9 times as great in the high transmittivity direction as in the low transmittivity direction.

14. The module of claim 13 further including means for rotating the polarizations of the energy entering the first crystal and leaving the second crystal relative to the crystals and the partial polarizers.

15. The module of claim 14 further including compensating means on the partial polarizer for compensating the tendency of the partial polarizer to rotate the polarization direction of optical energy incident thereon so that optical energy entering and leaving the partial polarizer has the same polarization direction.

16. The module of claim 12 further including means for rotating the polarizations of the energy entering the first crystal and leaving the second crystal relative to the crystals and the partial polarizers.

17. The module of claim 1 wherein the first and second crystals are wide field of view structures and each structure comprises in cascade along the optical axis a first birefringent crystal segment having a length one half the length of the crystal of the structure and a fast axis displaced 45° from the first direction in the normal plane, a half wave plate having an axis in the first direction in the normal plane, a second birefringent crystal segment having a length one half the length of the crystal of the structure and a fast axis displaced 90° from the fast axis of the first crystal segment in the normal plane.

18. The module of claim 17 wherein each structure further includes a quarter wave plate having an axis along the first direction, in the normal plane, the quarter wave plate in the structure downstream of the entrance polarizer in the module being downstream of the first crystal segment of the structure and downstream of the entrance polarizer of the module, the quarter wave plate in the structure upstream of the exit polarizer in the module being downstream of the second crystal segment of the structure and upstream of the exit polarizer of the module.

19. The module of claim 18 further including a first half wave plate downstream of the entrance polarizer and upstream of the first crystal, a second half wave plate upstream of the exit polarizer and downstream of the second crystal.

20. The module of claim 19 further including compensating means on the partial polarizer for compensating the tendency of the partial polarizer to rotate the polarization direction of optical energy incident thereon so that optical energy entering and leaving the partial polarizer has the same polarization direction.