1. The purpose of the BRF in the Mira cavity is to select the wavelength. There are three different types of filters used in this system of different thicknesses. Two of these filters are of a one-plate design and the other consists of a stack of three plates of certain thicknesses.

2. The fundamental operation of the BRF uses a property of the quartz crystal. The name itself, "bi-refringent", is indicative of the properties of the crystal. What this means is that the crystal will have two different refractive indices for the two orthogonal components of the polarized beam.

3. As the beam propagates through the quartz, its polarization state is constantly being rotated. By having a certain thickness of quartz, the polarization state of the output beam can be determined. Only horizontally polarized light can circulate in the Mira cavity. Light exiting the BRF with other polarization states will experience a loss at subsequent Brewster surfaces. As a result of the wavelength dependence of refractive index, only wavelengths that are rotated such that the light is horizontally polarized when the beam exits the BRF will be able to lase.

4. With the three-plate BRF, the bandwidth of transmitted light of the correct polarization state will be narrower (pico operation uses a bandwidth of around 0.5 nm) The two notch, single-plate BRF will allow transmission of a broad bandwidth of light for femto operation (bandwidths of 8 nm - 20 nm are used). For very short pulses, the single notch, single-plate BRF is used to allow much larger bandwidths to oscillate.

5. The BRF "filter stack" is glued into a holder which has a slot in its side to allow repeatability when removed and reinstalled. This holder slides into a securing ring and is held in place with one set screw. It may be slid in and out as required by the system alignment. The securing ring in turn fits onto the micrometer frame and is held by one screw. This securing ring has three holes through which the screw can go. The hole used in manufacturing (and hence that will correlate with the calibration data shipped with the system) is the uppermost hole. See Figure BRF(ii).

6. The orientation of the BRF, controlled by the micrometer drive, is very important as the BRF optic has more than one "order". These orders will allow the system to lase as normal and will give the same output power. The differentiating characteristic among the different orders is the tuning range. The tuning range can be determined if a monochromometer, wavemeter, or grating is available. The order that is desired is the first order.

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7. If none of the calibration sheets are available or if the system is being built, try to find the Zero Order to begin with. In the zero order, the BRF has no control of the wavelength, i.e., it is not acting as a tuning element. So if you look at the output wavelength, it should either not change at all or hop about randomly when the micrometer is tuned. If a grating is used, the first order (of the grating) beam diffracted from the grating will not move. **It is important to note that the system will modelock in this zero order but will be unstable and unreliable.** From this order, rotate the micrometer in a counter-clockwise direction until the Mira stops lasing and then begins to lase again. This will be the first order. This is the most accurate way of finding the first order. (If the micrometer is tuned more, it will stop lasing again and will enter the second order. With the higher orders, the tuning range will become smaller).

9. **Figure BRF(ii)** shows how the BRF optic will appear looking from behind the mount. The "Detail" section, at the top of the figure, shows how the BRF optic looks in the first order.

10. The calibration graph for the BRF micrometer setting versus wavelength generated in the factory will not correlate exactly with the values obtained at installation. This is a result of the intra-cavity beam being in a slightly different position in the BRF optic. It is obvious that the gradient (slope) of this graph will remain the same as the factory value. See the example overleaf. So what this means is that the BRF micrometer can be calibrated to the new values quite easily by calculating this offset.

11. To calculate the offset, tune the Mira to the peak of the wavelength range (maximum power). Go to the Test Series number given on the Customer Test Data Sheet. This will be of the form XXXX-XXXX-XXXX-XXXX, which is CW power - ML power - Peak wavelength - Pulse width (Fs). So from the value of the peak wavelength and the new micrometer reading, one point on the new BRF calibration graph is known. The difference between this micrometer reading and the factory micrometer reading for the same wavelength can be calculated. This is the offset. As the graph is approximately linear, this same offset can be used against every value of micrometer reading across the tuning range. This offset is typically quite small.
Figure BRF (i)

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When either of the single plate (Femto) BRF's are used in the zero order the optic will be approximately 10 degrees from its "square" position.

In Pico configuration using the three plate BRF the optic will appear as a Diamond shape as shown above.

**Figure BRF (ii)**

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MODULE 204D  BIREFRINGENT FILTERS

A doubly refracting or birefringent optical material has the property that within it the speed of light depends on the orientation (polarization) of the electric field vector with respect to a line or direction of crystal symmetry in the material called the Optics Axis. If the electric vector of the light is along the optic axis, the speed of that light is one value; however, if it is perpendicular to the optic axis, the speed of light is a different value. When light enters such an optical material, with a given electric vector orientation relative to the optic axis, the light can be treated as two separate wavefronts, advancing through the material at two different speeds. Upon leaving the birefringent material, the two waves recombine to form a resultant wave whose overall electric field vector orientation (polarization) may differ from that of the light wave entering the material. In general, birefringent materials can be used to change or control the polarization of the electric field vector of the light passing through the material.

Birefringent materials can be used to construct a filter for tuning the output wavelength of polarized lasers. The filter is constructed to allow light within a narrow range of wavelengths to pass without a change in its polarization. Light at all other wavelengths will undergo a polarization change that results in optical loss at polarizing surfaces in the optical system. Only for light at those wavelengths that experience no polarization shift will the losses be low enough for lasing to occur. Birefringent filters provide excellent tunability and are frequently used for continuous tuning of CW dye lasers. This module discusses the design and operation of birefringent filters for this application.

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Birefringence

The refractive properties of birefringent optical materials cannot be described by a single refractive index. In fact, there are two indices, referred to as the ordinary refractive index, $n_o$, for the ordinary ray traversing the birefringent crystal, and the extraordinary refractive index, $n_e$, for the extraordinary ray passing through the crystal. When a light ray is incident on a uniaxial birefringent crystal -- that is a crystal having a single optic axis --, the direction of the incident ray and the optic axis form a plane in the crystal. The electric field vector in the incident light can be resolved into components parallel and perpendicular to this plane. The latter component, the one polarized perpendicular to this plane and therefore always perpendicular to the optic axis, is the ordinary ray or O-ray. It propagates through the crystal with a single speed $v_o = c/n_o$ and refracts according to Snell's law. Its index of refraction is denoted as $n_o$. The other component -- the one parallel to the plane defined by the optic axis and the incident ray -- can be further resolved into components parallel to and perpendicular to the optic axis, which then will travel at different speeds through the crystal. This other component belongs to the extraordinary ray, or E-ray, which travels through the crystal with a net speed $v_e = c/n_e$ and direction different from that of the O-ray. Its index of refraction is denoted $n_e$.

The result of sending light into a uniaxial, birefringent crystal can be summarized by saying that the incident light ray is divided into two spatially separated emerging light rays, the O-ray and the E-ray. The O-ray always has its electric vector polarized perpendicular to the optic axis, while the electric vector of the E-ray is always polarized in some direction perpendicular to the O-ray.

![Fig. 4-16 Birefringence in a Uniaxial Optical Crystal](image-url)
In this figure, the plane of the optic axis (dashed line) and the incident ray is the plane of the paper, that is, same as the parallelogram drawn. In (a) the incident ray, an O-ray, is polarized in a direction perpendicular to the optic axis (depicted as black dots). It obeys Snell’s law and passes through the crystal undeviated. In (b) the incident light is polarized in -- or parallel to -- the plane of the optic axis and the incident ray (depicted as horizontal arrows). It is an E-ray and passes through the crystal along a bent path, as shown. In (c) unpolarized or natural light is incident upon the crystal. It is split into ordinary and extraordinary rays which travel through the birefringent material along different paths. Necessarily, as sketch (c) in Figure 4-16 illustrates, the emerging E- and O-rays are each *linearly* polarized and their vibrating electric fields are *perpendicular* to each other. Thus, passage of unpolarized light through a birefringent crystal can produce two distinct beams with crossed polarizations.

**WAVE PLATES**

Birefringent materials have several important applications in laser technology. In many cases the material is designed to operate as a *Wave plate*. In essence, a wave plate separates the incident light into O-ray and E-ray light which traverse the plate with different speeds and orthogonal polarizations. When they are recombined upon emerging from the waveplate, the polarization of the output beam can be significantly different from the polarization of the input beam.

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*Fig. 4-17 Effect of Half-wave Plate on Linearly Polarized Light*

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Figure 4-17 shows a *Half-wave Plate*. It is a piece of birefringent material cut with the optic axis lying in the plane of the back and front optical surfaces, as shown by the dashed lines. In this drawing, the optic axis is a direction from the lower right hand edge of the wave plate to the upper left hand edge. The thickness is chosen to produce a phase change of 180° between the ordinary and extraordinary rays as they complete one pass through the component. If light enters the half-wave plate polarized at 45° to the optic axis, its plane of polarization will be rotated through 90°.

Figure 4-18 illustrates how the half-wave plate works, if it is made of crystalline quartz, for example. When the incident light strikes the back surface, Figure 4-18a, it is resolved into two components with polarizations at right angles to one another. The component whose electric field is parallel to the optic axis is the extraordinary ray and has index of refraction \( n_e \). The ordinary ray is polarized in a plane perpendicular to the optical axis and has a different index of refraction, \( n_o \). For some materials (called positive uniaxial crystals) the ordinary ray is the faster and for others (called negative uniaxial crystals) the extraordinary ray is faster. In crystalline quartz used for laser wavelength tuning, the ordinary ray is the faster, as illustrated in the diagrams in this module. Crystalline quartz is positive uniaxial while calcite is negative uniaxial.
As the waves belonging to the O-ray and E-ray travel through the crystal, they continually become farther out of phase because one is traveling faster (and thus has a longer wavelength) inside the crystal. (See Figure 4-18b) The thickness of the half-wave plate is designed for a particular wavelength of light to produce a net phase shift of one-half wavelength between the two waves. When the light emerges from the half-wave plate, the phase of one wave will be changed by 180° with respect to the phase of the other wave. The two emerging waves then recombine to produce an output beam with a polarization that is shifted by 90° from the input light.

If the wave plate is cut to produce a phase shift of 90° between the two components, it is called a \textit{Quarter-wave Plate} and will change linearly polarized light to circularly polarized. Quarter-wave plates will be discussed in Module 206D, "Electro-optical Mechanisms."

\textbf{WAVE PLATE TUNING}

The wave plate used for laser tuning is a \textit{Full-wave plate}. Figure 4-19a shows the effect of this component on vertically polarized light of the \textit{design wavelength}. The slow wave is retarded by exactly one full wavelength inside the material and therefore no change in polarization occurs. For light of wavelengths different than the design wavelength the retardation of the slow wave is more or less than one full wave. Figure 4-19b shows such light emerging from the wave plate. The phase difference between the two components results in elliptically polarized light. If this light passes through another polarizer with its

\begin{figure}
\centering
\includegraphics[width=\textwidth]{fig4-19.png}
\caption{Effect of Full-wave Plate at Design Wavelength and Another Wavelength}
\end{figure}

\textbf{Fig. 4-19} Operation of Full-wave Plate
transmission axis oriented vertically, the polarizer will reject the horizontal component of this light and introduce sufficient loss to prevent lasing at this wavelength. Hence, the full-wave plate tuner favors only the design wavelength at which the laser is meant to operate.

Figure 4-20 shows a wave plate designed for tuning a CW dye laser. It is mounted in the laser cavity at Brewster's angle to eliminate reflections for vertically polarized light while introducing loss for horizontally polarized components. The thickness of the crystal is chosen to give full-wave retardation at Brewster's angle. For a given orientation of the wave plate, only a very narrow range of wavelengths will suffer negligible loss in passing through the wave plate. All others will be subject to considerable loss and prevented from lasing.

![Fig. 4-20 Operation of a Birefringent Tuning Filter](image)

The wave plate is tuned for low loss at other wavelengths by rotating it about the normal to the wave plate surface. Four possible orientations of the optic axis -- A, B, C, D -- shown in Figure 4-20. Rotating the wave plate has no effect on the Ordinary index of refraction, but the Extraordinary index changes with each new direction of the optic axis. Rotating the wave plate thus changes the speed of the extraordinary wave, thereby selecting a new wavelength at which no change in polarization occurs.

A single wave plate used to tune a CW dye laser in the visible region of the spectrum will result in a laser linewidth of about 0.3 nm. Greater tunability may be achieved by using additional plates, each twice the thickness of the preceding plate. The additional wave plates provide a longer path inside the material for the unwanted wavelengths to become out of phase and also introduce additional reflection losses for the horizontal components since they act as a stacked plate polarizer. Figure 4-21 illustrates the laser linewidth with one, two
Fig. 4-21  Tunability of Birefringent Filters for Dye Lasers

and three elements. Birefringent filters are widely used to tune CW dye lasers because of their high tunability and low loss for the tuned wavelength.

SUMMARY

A birefringent filter is a full-wave plate mounted in the laser cavity at Brewster's angle. Polarized light striking the wave plate is resolved into two components that travel through the material at different speeds. Light of one specific wavelength will experience no change in polarization when it passes through the filter. All other wavelengths will emerge as elliptically polarized light with a horizontal component. This component is rejected by Brewster's angle polarizing surfaces in the optical system, thereby imposing a loss on all wavelengths except the one desired. The tunability of a birefringent filter can be improved by increasing the number of wave plates, where each wave plate is twice the thickness of the preceding plate. These filters are frequently used for tuning CW dye lasers because they produce the narrowest linewidth of any wavelength selection mechanism and introduce little optical loss for the desired wavelength.