AIP | Journal of Applied Physics

Line narrowing and tuning of high-power Nd: glass laser using an an intracavity brewster-angle birefringent filter

Yung S. Liu

Citation: Journal of Applied Physics **48**, 647 (1977); doi: 10.1063/1.323702
View online: http://dx.doi.org/10.1063/1.323702
View Table of Contents: http://scitation.aip.org/content/aip/journal/jap/48/2?ver=pdfcov
Published by the AIP Publishing

Line narrowing and tuning of a high-power Nd:glass laser using an intracavity Brewster-angle birefringent filter

Yung S. Liu

General Electric Corporate Research and Development, Schenectady, New York 12301
(Received 13 May 1976)

We discuss the properties of a Brewster-angle birefringent filter (BBF) used inside a laser cavity for line narrowing and tuning of a high-power low-gain laser, in particular, a Nd:glass laser. The free-spectral range (FSR) and the dispersion function are found to be strongly angle dependent. This tuning method is found to be extremely simple, rugged, almost lossless, and to have a high finesse. The technique is, of course, suitable for other high-power wideband lasers such as dye lasers.
PACS numbers: 42.60.Fc, 42.80.Cj

I. INTRODUCTION

Recent interest in resonant scattering and laser-induced chemical reactions, among others, requires high-power laser sources which are tunable and spectrally narrowed. Most tuning methods are found to be less than completely satisfactory when applied to a high-power low-gain laser such as a Nd: glass laser. Methods such as a prism, grating, Fabry-Perot etalon, and other electro-optical and acousto-optical methods suffer disadvantages of having low damage threshold, high loss, small tuning range, and/or are difficult to operate. Birefringent materials have drawn much attention recently and are found to be an attractive tuning method.[1-6] In this paper we discuss some properties of a Brewster-angle birefringent filter (BBF) used inside a laser cavity for line narrowing and tuning of a high-power low-gain laser, in particular, a Nd: glass laser. We have found that the operation of a single BBF is extremely simple, rugged, and almost lossless. The free-spectral range (FSR) and the dispersion function are found to be angle dependent. Expressions for these functions are given and compared with experimental results obtained using a $LiNbO_3$ plate and a deuterated KDP plate for line narrowing of a Nd: glass laser.

II. ANALYSIS

Consider a coordinate system shown in Fig. 1 in which the wave vector k is coincident with the optical axis of the laser cavity and the x axis is the optical axis of a uniaxial crystal plate. ϕ is the angle between the wave vector k and the direction normal to the birefringent plate and is at Brewster's angle. θ is that between the optical axis of the birefringent material and the polarization direction of the laser oscillation. The directional cosine (α, β, γ) of the wave propagation in this coordinate system in a plane-wave approximation can be expressed in terms of θ and ϕ as

$$\alpha = \sin\phi\cos\theta, \quad \beta = -\sin\phi\sin\theta, \quad \gamma = \cos\phi. \tag{1}$$

The equation of a plane-wave propagation is given by

$$\alpha x + \beta y + \gamma z = 0. \tag{2}$$

The expression for the ellipsoidal wavefront generated by the plane wave entering the birefringent crystal is expressed by

$$\eta_1^2 x^2 + \eta_2^2 y^2 + \eta_3^2 z^2 = 1, \tag{3}$$

where $\eta_1 = n_0$, $\eta_2 = \eta_3 = n_e$ for an extraordinary wave, and $\eta_1 = \eta_2 = \eta_3 = n_0$ for an ordinary wave. The wavefront of the propagating plane wave inside the crystal through any point (x_0, y_0, z_0) subjected to the constraint given by Eq. (3) is

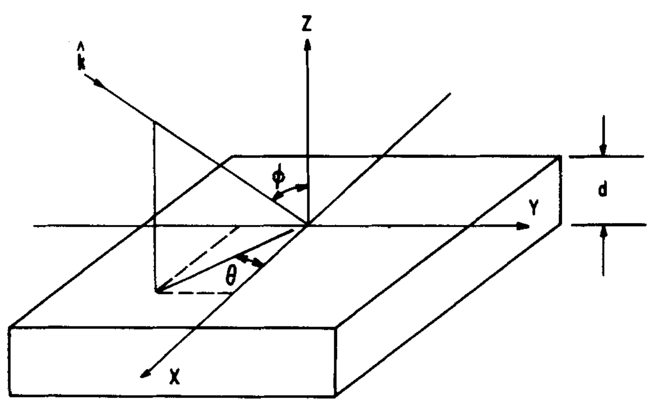
$$\eta_1^2 x_0 x + \eta_2^2 y_0 y + \eta_3^2 z_0 z = 0. \tag{4}$$

By matching the boundary condition at $z = 0$, the equation of a plane wave propagating inside the crystal can be expressed in terms of its directional cosine (α, β, γ) and the refractive indices (η_1, η_2, η_3) of the crystal as

$$\alpha x + \beta y + \eta_3 \left(1 - \frac{\alpha^2}{\eta_1^2} - \frac{\beta^2}{\eta_2^2}\right)^{1/2} z = 0. \tag{5}$$

Therefore, the phase difference $\Delta\Phi$ between an extraordinary wave and an ordinary wave after traveling a distance $z = d$, equal to the thickness of the crystal, is

$$\Delta\Phi(\theta,\phi) = \frac{d}{\lambda}\,\delta n(\theta,\phi) = \frac{d}{\lambda}\left[n_e\left(1 - \frac{\sin^2\phi}{n_e^2(\theta)}\right)^{1/2} - n_0\left(1 - \frac{\sin^2\phi}{n_0^2}\right)^{1/2}\right], \tag{6}$$



THE COORDINATE SYSTEM OF A UNIAXIAL BIREFRINGENT CRYSTAL

FIG. 1. The coordinate system used for a uniaxial birefringent crystal; the x axis is the optical axis of the crystal and the wave vector k is the optical axis of the cavity. θ is the angle between the polarization of the laser oscillation and the crystal optical axis.

where

$$n_e^2(\theta)=\left(\frac{\cos^2\theta}{n_0^2}+\frac{\sin^2\theta}{n_e^2}\right)^{-1}. \tag{7}$$

The free-spectral range, FSR(θ, ϕ), of a BBF is, therefore, a function of θ and ϕ and can be expressed by

$$\mathrm{FSR}(\theta, \phi)=\frac{\lambda^2}{d\delta n(\theta, \phi)}=\frac{\lambda}{\Delta\Phi(\theta, \phi)}. \tag{8}$$

The angular dispersion relation, $S(\theta, \phi)$, which defines the rate of change of the peak of the passband as a function of the angular position θ for a given ϕ can easily be shown to be

$$S(\theta, \phi)=\frac{1}{\Delta\Phi^2(\theta, \phi)}\;\frac{\delta nd(\sin^2\phi)(\sin 2\theta)}{\lambda n_0^2\{1-(\sin^2\phi/n_e^2(\theta))\}^{1/2}} \quad \text{for } n_e\approx n_0, \tag{9}$$

where $\delta n=|n_e-n_0|$. From Eq. (9) it is seen that the dispersion function has a maximum at $\theta=45°$, namely, for the case that the projection of the laser polarization is at 45° with respect to the optical axis of the crystal for a given value of ϕ. The angular dispersion relation given by Eq. (9) defines the angular displacement required to scan over a wavelength range of interest for given values of ϕ and θ. This function is useful when an external programmable tuning is desired.

III. EXPERIMENT

In the experiments, a Brewster-angle Pockels-cell was used for Q switching. The Nd:glass oscillator was a slab type of dimension 6×15×260 mm with Brewster faces at both ends.[7] The Brewster ends eliminate the need for additional polarizing elements. The optical path inside the active medium undergoes total internal reflection. Such a configuration gives a distortion-free linearly polarized beam at a repetition rate up to 10 pulses/sec with an output energy of 0.5 J. The output spectrum was analyzed with an 1-m Jarrel-Ash spectrometer and displayed with a silicon-vidicon camera.

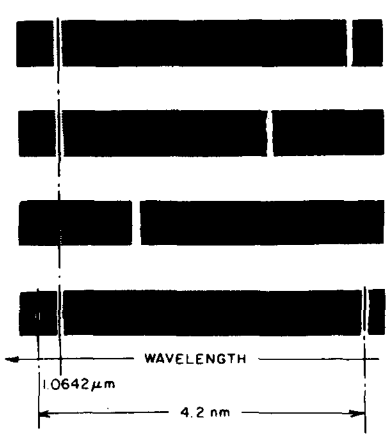


FIG. 2. The tuning range of a line-narrowed Nd:glass laser obtained by using a $LiNbO_3$ Brewster-angle birefringent filter. The FSR is 4.2 nm. A Nd:YAG laser line at 1.0642 μm is shown for the calibration. The tuning is accomplished by varying θ. The spectra were imaged with a silicon-vidicon camera and photographed directly from a monitor. The resolution of the imaging system was limited by the monitor to be about 0.1 nm. The photographs were overexposed and thus show a variation in the linewidth.

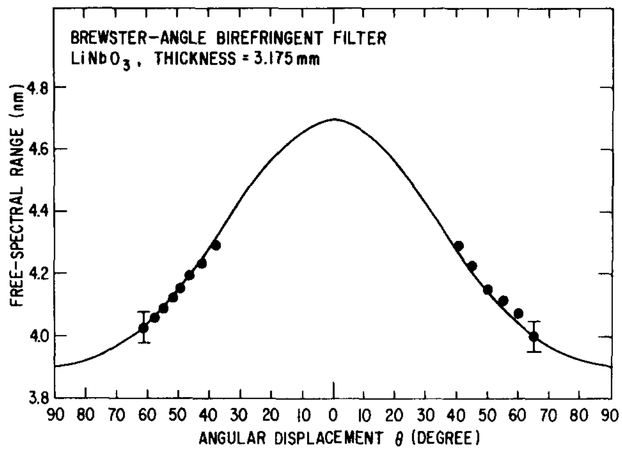


FIG. 3. Variation of the FSR as a function of θ (defined in the text). The Brewster-angle birefringent filter is an x-cut $LiNbO_3$ (3.175 mm thick). $n_0=2.2463$, $n_e=2.1627$, and $\phi=66.0°$. The solid curve is drawn from Eq. (8) and the measured values are shown as dots. The resolution was limited to about 0.1 nm by the monitor.

The spectrum of the Q-switched glass laser normally has a spectral bandwidth (fullwidth at half-maximum value) about 2.5 nm centered at 1.061 μm at a pumping level about two times above the threshold value for the oscillation onset. The spectral width is broadened as the pumping power increases. An x-cut $LiNbO_3$ crystal (3.175 mm thick) was placed inside the cavity for line-narrowing measurements. The birefringent plate was included at Brewster's angle with respect to the optical axis of the cavity. The line narrowing and tuning of the glass laser output are shown in Fig. 2 in which a Nd:YAG laser line at 1.0642 μm is shown for the calibration. A FSR of 4.2 nm is shown in Fig. 2(d) with this particular tuning element. As shown in the figure, the linewidth of the oscillation is about 0.1 nm, which gives a finesse of about 40. The spectral width can be further narrowed down to less than 0.05 nm by placing additional low-finesse solid glass etalons inside the cavity. Due to the inclination of a BBF, the FSR is found to be dependent upon angle of θ as well as ϕ. The FSR was measured as a function of θ for a given ϕ and is shown in Fig. 3.

It is interesting to note that a variable FSR tuned by a single birefringent element can provide a simple method to generate a tunable difference frequency using optical mixing techniques.[8-11] Several other birefringent materials have been used for line narrowing of a Nd:glass laser. Among them, a 3-mm-thick 98% deuterated KDP plate gives a FSR of approximately 8 nm with an oscillation linewidth of about 0.3 nm at a pumping level within 50% above the threshold value. The insertion loss of the KDP plate was determined by threshold measurements and was found to be negligible. No damage was observed at a power density estimated to be greater than 500 MW/cm^2 inside the cavity. Neither did it show any spectral shift due to thermal effects. The latter effect for a birefringent filter is expected to be of the second order as compared with that for a solid or air-gap Fabry-Perot etalon.

In summary, we have shown that a single BBF provides an extremely simple, rugged, and low-loss intracavity tuning element, which is particularly suitable for a high-power low-gain laser oscillator such as a Nd:glass laser. We have shown that the free-spectral range and the angular dispersion function depend upon the angular displacement of θ, defined in Fig. 1. Furthermore, the electro-optical property of the material can be used for the rapid tuning of a laser output. The technique is, of course, suitable for other high-power wideband lasers such as dye lasers.

[1]J.W. Evans, J. Opt. Soc. Am. 39, 229 (1949).
[2]H. Walther and J.C. Hall, Appl. Phys. Lett. 17, 239 (1970).
[3]H. Gerlach, Opt. Commun. 8, 41 (1973).
[4]A.L. Bloom, J. Opt. Soc. Am. 64, 447 (1974).
[5]M. Okada, S. Shimizn, and S. Leiri, Appl. Opt. 14, 917 (1975).
[6]D. Kato and T. Sato, Opt. Commun. 5, 134 (1972).
[7]W.B. Jones, L.M. Goldman, J.P. Chernoch, and W.S. Martin, VII International Quantum Electronics Conf., Montreal, 1972, Paper C 9 (unpublished).
[8]D.H. Auston, A.M. Glass, and P. LeFur, Appl. Phys. Lett. 23, 47 (1973).
[9]R.L. Aggarwal, B. Lax, and G. Favrot, Appl. Phys. Lett. 22, 329 (1973).
[10]K.H. Yang, J.R. Morris, P.L. Richards, and Y.R. Shen, Appl. Phys. Lett. 23, 669 (1973).
[11]T. Yajima and K. Inoue, Phys. Lett. A 26, 281 (1968).