Fast Electro-Optic Wavelength Selection and Frequency Modulation in Solid State Lasers

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■ Electro-optic devices permit rapid wavelength selection and high-bandwidth frequency modulation in single-frequency solid state lasers. Laser dynamics limits both the speed of wavelength selection and the linearity of frequency modulation. The maximum speed of laser mode selection is determined by the buildup of oscillation from spontaneous emission. For frequency modulation, the minimum fractional deviation from chirp linearity is the ratio of the cavity round-trip time to the duration of the chirp. Nd:YAG and Ti:Al_2O_3 lasers built at Lincoln Laboratory have attained these theoretical limits.

Some laser applications, including coherent communications and coherent radars, require lasers with attributes such as operation on a single laser mode, frequency stability, high-speed tuning, and large-bandwidth frequency modulation. Single cavity mode operation can be achieved by using a material with a homogeneously broadened laser transition in a properly designed cavity. Frequency stability to extraordinary levels is now possible [1]; solid-state lasers with their frequencies locked to one part in 10^{14} have been operated [2], although frequency stability of one part in 10^8 is usually sufficient for the above applications. In our work, high-speed tuning has been obtained by using electro-optic elements for frequency selection. Large-bandwidth frequency modulation has also been realized by using electro-optic phase modulators inside the laser cavity. This article describes the design limits, the principles of operation, and the performance of electro-optically tuned solid state lasers, with an emphasis on single mode operation, fast wavelength selection, and large-bandwidth frequency modulation.

The lasers described in this article are free-running single-mode lasers, whose frequency v is determined by the round-trip optical path length L in the laser cavity and the longitudinal mode number N, where

$$v = \frac{Nc}{L}, \tag{1}$$

and where c is the speed of light. Equation 1 shows that adjacent longitudinal modes are separated by a frequency difference of c/L, which is the cavity free spectral range, and the fractional frequency stability ($\delta v/v$) equals the fractional length stability ($\delta L/L$). Thus a trade-off between bandwidth within a single longitudinal mode and frequency stability is apparent. For example, to obtain frequency stability of 10^{-8}, the length stability of a 1-m cavity must be 10 nm, but a 1-cm cavity must be stable to 0.1 nm. On the other hand, frequency deviations of more than 300 MHz in the 1-m cavity eventually cause mode switching, whereas frequency deviations of 30 GHz are possible in the 1-cm cavity. We use a long cavity when frequency stability and a number of tuning elements are needed and a short cavity when a large frequency modulation is needed.

Electro-optic tuning elements allow frequency control that is similar in many respects to mechanical tuning elements, but at a higher speed. A tuning element of either type minimizes loss in the laser cavity only at

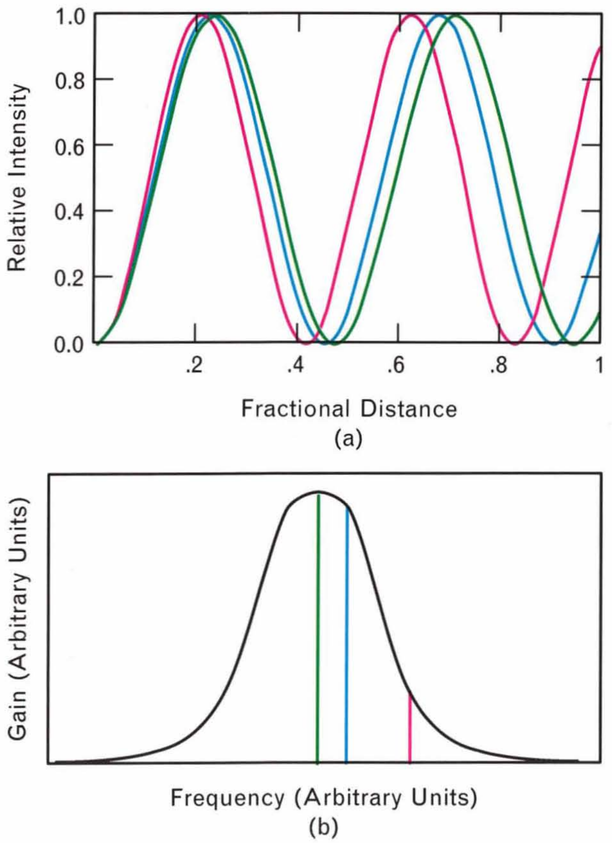


FIGURE 1. Spatial hole burning. This figure illustrates why a laser with spatial hole burning can still operate in a single frequency. (a) The intensity distribution of three possible laser cavity modes is given for the region between the cavity mirror and the end of the gain medium. The red mode number is much larger than the green mode number, and the blue mode number is slightly larger than the green mode number. The green mode, whose frequency is at the peak of the gain, is assumed to be lasing. Because of its greater frequency offset from the green mode, the red mode has more intensity than the blue mode in regions where the green mode intensity is weakest. As a result the red mode interacts with a larger population inversion, which has not been depleted by the green mode, so the red mode is more likely than the blue mode to lase simultaneously with the green mode for a laser with uniform gain versus frequency. (b) The frequencies of the modes given in (a) are shown with the unsaturated gain profile. For the narrow gain peak shown, the red mode can experience insufficient gain to lase. Thus, if the gain medium abuts a cavity mirror, the combination of large spatial overlap for nearby modes and the narrow gain bandwidth can force a laser to operate in a single mode.

certain wavelengths, and a cascade of several tuning elements can provide unique cavity mode selection. Electro-optic tuning elements, however, respond quickly to an applied voltage so that laser dynamics rather than response time limits the speed of mode switching. High-slew-rate, high-voltage power supplies are needed to control the tuning elements for such fast mode switching. Although frequency modulation is possible at a higher speed than mode switching, laser dynamics, not the power supplies, also limits the linearity of the voltage-to-frequency conversion. The use of electro-optic phase modulators gives fast control of the optical path length in the laser cavity; thus the single-frequency output can be stabilized or frequency modulated, depending on the requirements.

Single-Frequency Lasers

The spectral profile of the gain medium, the tuning elements, and the other optical elements in the cavity determine the laser longitudinal mode [3]. To simplify single-frequency operation the following three conditions should be met: gain occurs on a homogeneously broadened transition, spatial hole burning is absent, and wavelength selection is strong.

There are two classes of broadening of optical transitions—homogeneous and inhomogeneous. In homogeneous broadening all transitions are centered at a given frequency and participate equally in the lasing process. A laser using a homogeneous transition tends to operate only at the frequency with the highest small-signal gain, and the gain is clamped at all other frequencies. By contrast, in a laser that employs an inhomogeneous transition, only the excited states that give a particular transition frequency participate in single-frequency lasing. The other excited states can give net gain for other modes, resulting in multimode operation. Therefore, single-frequency lasing is relatively inefficient for inhomogeneous transitions. In our work, $Ti{:}Al_2O_3$ and Nd:YAG lasers, both of which involve homogeneous transitions, have been operated efficiently as single-frequency lasers.

Even for a homogeneously broadened transition, multimode operation can occur because of spatial inhomogeneities in the optical waves. A standing-wave laser cavity operating in a single frequency has an electric field with nodes at the end mirrors and at every half-wavelength interval from the mirrors. The depletion of the population inversion in those regions near electric maxima, and not in regions near the electric field nodes, is referred to as spatial hole burning and occurs in both the

Table 1. Frequency-Selective Filters for Visible or Near Infrared Tuning.

The values given indicate typical characteristics for such devices. In actual implementations the values will differ from typical values given here by a factor of 3. Frequency spacing refers to the frequency difference between transmission maxima for the filter, frequency uncertainty refers to the resettability of a laser using this filter, and the loss is the single-pass loss.

Frequency Filter	*Basis of Operation*	*Frequency Spacing* (cm^{-1})	*Frequency Uncertainty* (cm^{-1})	*Loss (%)*
Prism	Dispersion	∞	10	0.2
Wave plate	Birefringence	1000	3	0.2
Grating	Diffraction	10,000	0.3	10
Etalon	Interference	0.3	0.003	0.5

population inversion and the gain [4]. Because excess gain builds up in the regions near the nodes, frequencies that have electric field antinodes close to the positions of the nodes of the first mode can often lase.

A unidirectional ring-laser cavity can be used to eliminate spatial hole burning. In this laser the electromagnetic wave travels in one direction around the cavity, so the electric field amplitude is uniform along the axis of the gain medium.

A narrow homogeneous linewidth together with a large free spectral range can force single-frequency operation even in a standing-wave laser cavity [5]. Also, cavities with a free spectral range larger than the homogeneous gain linewidth can operate at a single frequency if the gain medium is sufficiently short and is placed at one end of the cavity [6]. Assuming that the laser begins operation in a single mode, the other cavity modes also have a node at the end mirror and cannot take advantage of the excess gain caused by spatial hole burning. As Figure 1 shows, nearby cavity modes compete for the same population inversion and so do not see the excess gain. Cavity modes further from the peak of the gain do see a larger population inversion, but do not lase because the gain has fallen from the peak value.

Frequency Selection

Frequency filters can be used in laser cavities to select the longitudinal mode number N. Table 1 presents typical characteristics for the most common frequency filters—prisms, wave plates, gratings, and etalons. A grating, because it has excellent frequency selectivity, can force single-frequency operation [7, 8]. The large reflection loss in a grating, however, makes it suitable only for high-gain lasers. Low-gain lasers, which include continuous-wave $Ti:Al_2O_3$ lasers and continuous-wave Nd:YAG lasers, require low-loss intracavity optical components such as prisms or wave plates for coarse tuning and etalons for fine tuning.

Frequency filters that respond quickly to an external drive can allow fast frequency selection [9–11]. Mechanical tuning with fast galvanometers can occur in 1 msec; acousto-optic tuning can be done more quickly, although no faster than 1 μsec. Electro-optic materials change their refractive indexes in approximately 1 psec, which is so rapid that laser dynamics limits the speed of electro-optic tuning. For diode lasers an additional limit on fast electro-optic tuning occurs because the finite junction resistance causes slow thermal tuning [8]. The electro-optic devices we use dissipate a negligible amount of electrical and optical power, and the thermal tuning is not significant.

Electro-optic tuning elements have a drawback in that the refractive index depends weakly on the applied electric field. The refractive index changes by

$$\delta n = \frac{n^3 r}{h} \delta V , \qquad (2)$$

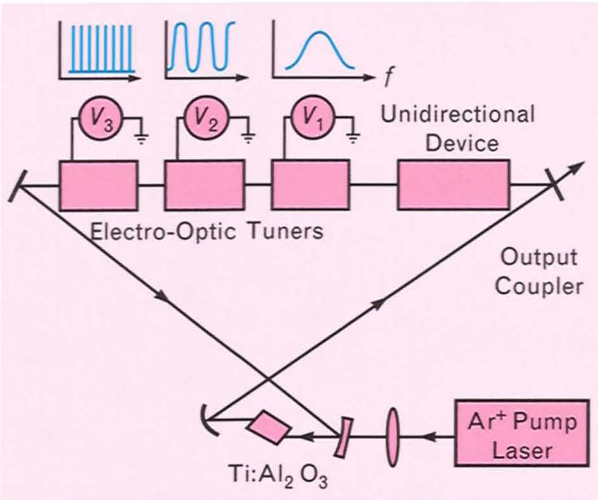


FIGURE 2. Single-frequency $Ti:Al_2O_3$ ring laser. A unidirectional device forces the light wave to travel in one direction around the ring. The resulting traveling wave uniformly depletes the gain region, so spatial hole burning is not present. Several stages of electro-optic frequency filters (e.g., wave plates and etalons) provide coarse and fine tuning to select the frequency.

for a change in voltage δV across a crystal of height h. The electro-optic coefficient r depends on the material and the orientation of the crystal axes relative to the light polarization direction and the applied field [12]. Commonly used electro-optic crystals of $LiTaO_3$, $LiNbO_3$, and AD*P have refractive index changes of approximately 10^{-4} when placed in an electric field of 10^6 V/m. Although other materials with larger electro-optic coefficients exist (e.g., $KNbO_3$), either low light levels damage the material (photorefractive damage), or the material absorbs light in the region of interest, or the material is difficult to grow. The material must be chosen so that the transmission loss is small, allowing the tuning element to be placed in the laser cavity with little effect on the lasing.

$Ti:Al_2O_3$ lasers, discovered at Lincoln Laboratory [13], have the largest tuning range of any laser. Assuming coverage of a large fraction of the $Ti:Al_2O_3$ tuning range, a laser having a 1-m-long cavity can operate in any of several hundred thousand longitudinal modes. Figure 2 shows a schematic diagram of a tunable, single-frequency $Ti:Al_2O_3$ ring laser [14]. The cavity includes the gain medium, mirrors for feedback, tunable filters to select the frequency, and a unidirectional element to ensure traveling-wave operation (which prevents spatial hole burning). The unidirectional device has a larger loss in one direction of travel around the ring than in the other direction, and the laser operates in the direction with the lowest loss. Although an acousto-optic beam deflector can provide traveling-wave operation [15], the laser cavity requires apertures large enough (3 mm) to provide low loss for the acousto-optically diffracted beam; the clear aperture of some of the electro-optic tuners is insufficient. Therefore, to force unidirectional operation in our system, a Faraday rotator and an optically active rotator were used [16].

Electro-optic wave plates and etalons provided the fast frequency tuning. A wave plate is a birefringent crystal with its optic axis oriented at 45° relative to the polarization direction of the incoming light. A wave plate placed between parallel polarizers acts as a coarse frequency filter. Transmission maxima occur at those frequencies for which the optical-path-length difference for the orthogonal polarizations in the birefringent crystal is an integral number of wavelengths:

$$(n_e - n_o)l = M\lambda, \tag{3}$$

where n_e and n_o are the indexes of refraction for the extraordinary and ordinary rays respectively, l is the crystal length, and M is an integer order number. For frequencies that do not satisfy this condition, the polarization is rotated, the polarizers reduce transmission through the filter, and the increased loss prevents lasing.

Figure 3(a) shows the effect of adding a 12th-order wave plate ($M = 12$ in Equation 3) between two Brewster-angle windows in a $Ti:Al_2O_3$ laser cavity. The laser operates near the frequency selected by the wave plate, 12,470 cm^{-1}, but the frequency is slightly shifted by the $Ti:Al_2O_3$ gain profile. If we ignore the small frequency-pulling effects, the laser tuning curve derived from Equations 2 and 3 is

$$\delta\lambda = \frac{n^3 r}{M} \frac{l}{h} \delta V. \tag{4}$$

Increasing the length-to-height ratio of the wave-plate crystal increases the tuning for a given voltage change. The height of the crystal, however, must be larger than the laser beam size, and the length must be short enough so that absorption in the electro-optic crystal does not degrade laser performance. The length-to-height ratio selected in our experiments was 7.

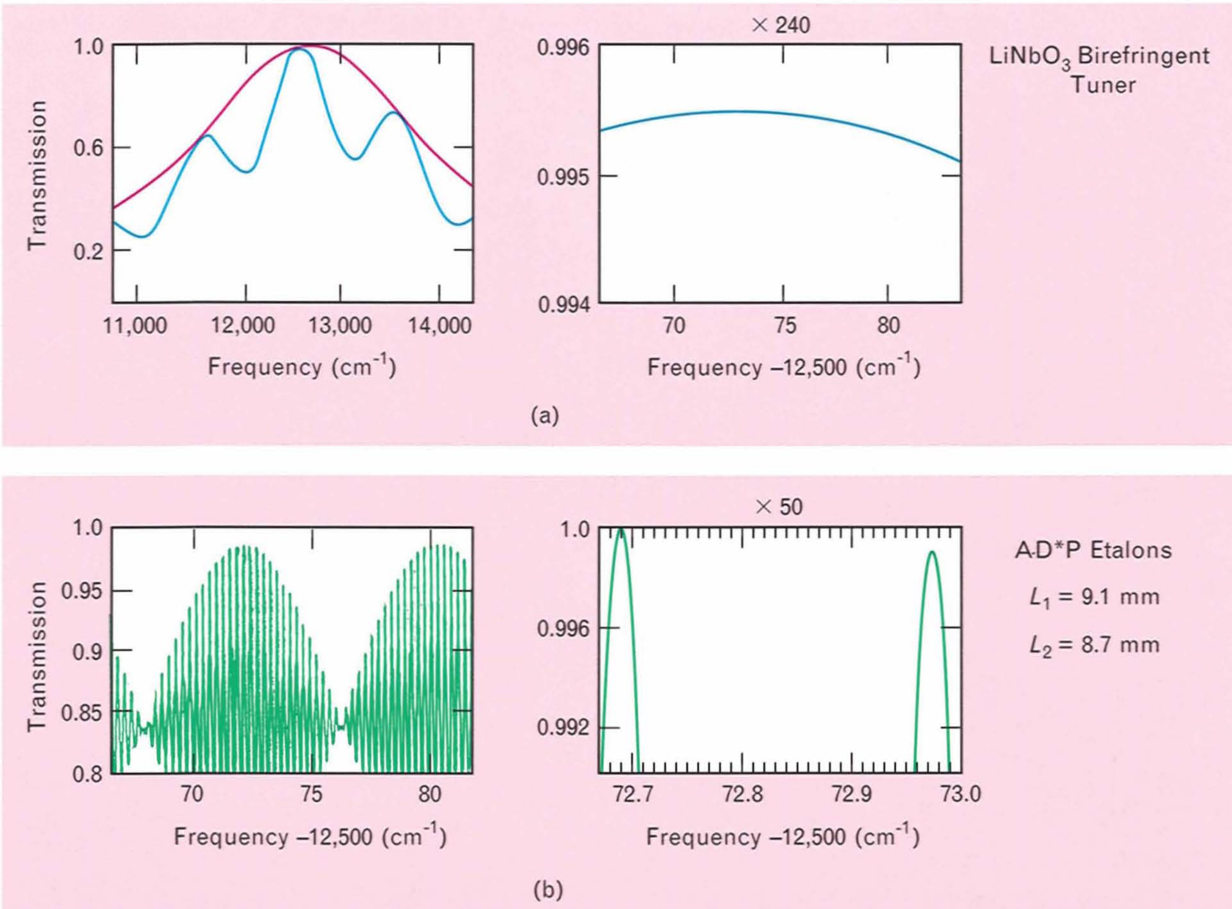


FIGURE 3. Frequency selection characteristics of electro-optical tuning elements in a $Ti{:}Al_2O_3$ laser. (a) The red curve displays the gain spectral profile of the $Ti{:}Al_2O_3$ medium. To achieve frequency selection, the gain is filtered by the frequency-selective elements, which are a birefringent tuner and two etalons. The blue curve shows the product of the gain curve and the birefringent tuner. When the product curve is expanded in frequency by 240 (right side), the frequency selectivity appears poor. (b) Two etalons provide more frequency selectivity. An expansion by 50 (right side) shows frequency selection between cavity longitudinal-mode frequencies, as indicated by hatch marks on the frequency scale.

The electro-optic wave plate we used consisted of an electrically controllable $LiNbO_3$ crystal and a quartz 12th-order wave plate at 800 nm. These plates were placed between partially polarizing Brewster-angle windows. A voltage applied across the $LiNbO_3$ crystal causes a linear change in the plate wavelength transmitted (see Equation 4) with a slope of 0.03 nm/V. To change the birefringence by one wavelength required 1700 V. The laser can operate at a given wavelength by adjusting the voltage. The tuning range is limited to the wavelength divided by the order number.

Electro-optic etalons were used for the fine frequency filters. In contrast to a mechanical etalon, an electro-optic etalon requires no tilting, and thus maintains the laser alignment. The relation between the frequency shift δv and the change in applied voltage is

$$\delta v = \frac{v n^2 r}{h} \delta V .$$

The etalon free spectral range $c/(2nl)$ is the frequency spacing between two transmission maxima. To tune one etalon free spectral range requires a voltage of

$$\delta v = \frac{v n^2 r}{h} \delta V . \tag{5}$$

To tune a short etalon—where the length is smaller than

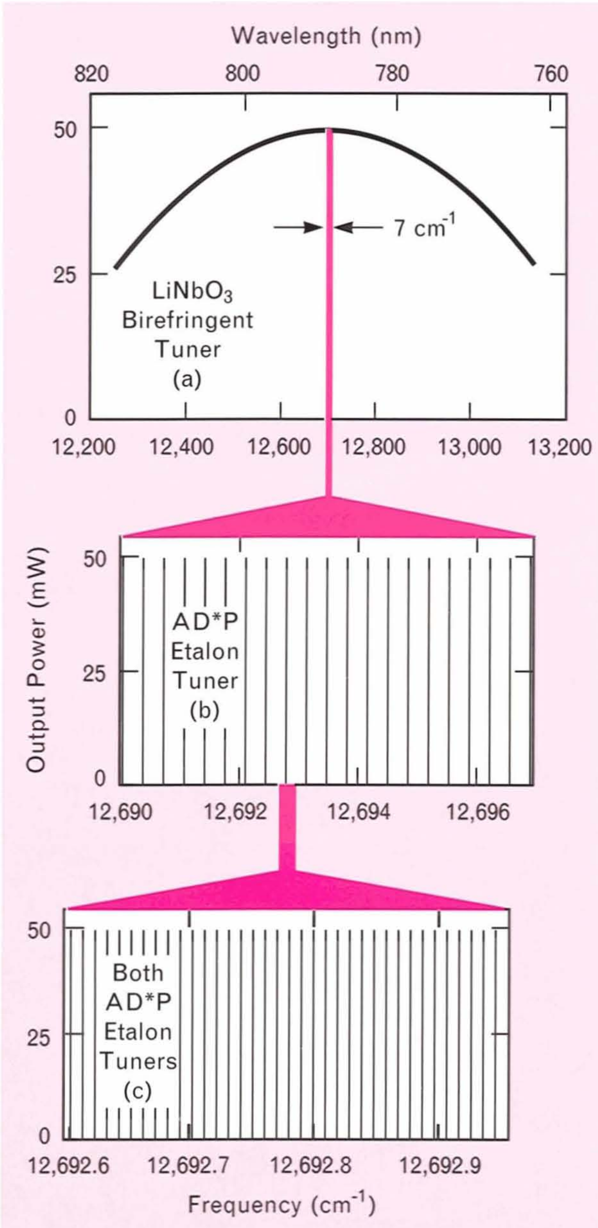


FIGURE 4. Electro-optic tuning of a single-frequency $Ti:Al_2O_3$ laser. (a) Using only the birefringent tuner, the laser accesses single modes over a 900-cm^{-1} region with jumps of 7 cm^{-1}, which is the free spectral range of the effective 0.4-mm etalon. The output power varies by a factor of 2, from 50 mW in the center to 25 mW in the wings of the tuning range. Later experiments with a better argon-ion laser pump source gave an output power of 300 mW at the peak of the tuning range. (b) Electro-optic control with one etalon generates frequencies over the 7-cm^{-1} region. The frequencies are separated by the free spectral range of 0.35 cm^{-1} of the other etalon. (c) Simultaneous tuning of the two etalons gives access to each longitudinal mode within the 0.35-cm^{-1} range.

the height—one free spectral range, the voltage applied must exceed the breakdown voltage. The coarse tuning characteristic of a short etalon, however, can be obtained with two long etalons whose length difference is small. The optical-path-length difference of the two long etalons effectively acts as a short etalon.

Our electro-optic etalons were AD*P crystals 8.7 mm and 9.1 mm in length. The etalons provided a tuning range of 7 cm^{-1}, which corresponds to the free spectral range of a single 0.4-mm-long etalon. With a length-to-height ratio of 3, a voltage change of 2.4 kV was required to access any mode within the free spectral range of the combined thick etalons (see Equation 5). Figure 3(b) shows the transmission function of the pair of thick etalons. This transmission function is different from the transmission function of a thin-etalon and thick-etalon pair, but is just as effective at selecting a single frequency.

Figure 4 shows how the etalon pair and the wave plate can tune to any frequency within a 900-cm^{-1} band. Thus the electro-optic tuning system accesses 10^5 longitudinal modes of a 1-m laser. Figure 4(a) shows the tuning curve obtained by applying a voltage only to the wave plate. Figure 4(b) shows the tuning curve obtained by applying a voltage to only one of the electro-optic etalons. The laser frequency-hops by the free spectral range of 0.35 cm^{-1}, which is the free spectral range of one of the thick etalons. The laser intensity remains constant over the tuning interval. Figure 4(c) shows the tuning curve when the voltage is applied to both electro-optic etalons. The effect is that of having a fixed short etalon and a scanned longer etalon. In this case the laser hops by the free spectral range of the laser cavity, which is 0.01 cm^{-1}. Again the laser intensity remains constant over the tuning range.

To verify that the laser can indeed access every longitudinal mode, frequencies were selected at random within the 900-cm^{-1} tuning range. Nearly all of these frequencies lased, except for the modes that coincided in frequency with absorption lines of atmospheric oxygen.

Mode Switching

Although electro-optic filters respond quickly to an applied voltage, cavity dynamics limits the speed with which the single-frequency laser can be tuned. For example, with our electro-optic tuners the laser frequency

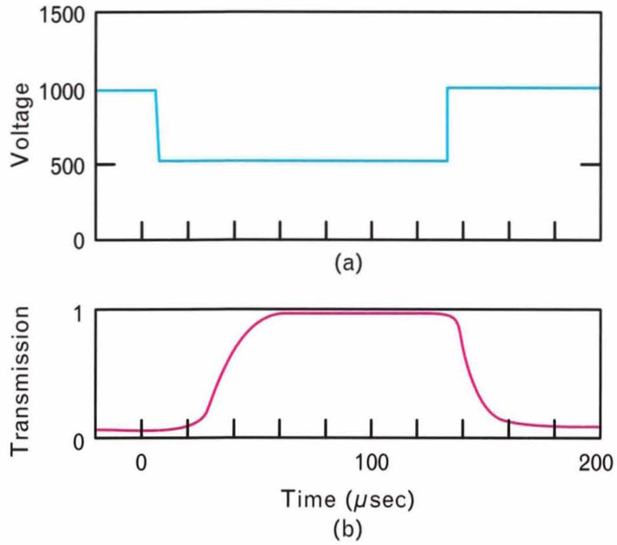


FIGURE 5. Mode switching of a single-frequency laser. (a) The voltage waveform applied to the electro-optic etalon selects a new laser mode. (b) Transmission through a fixed Fabry-Perot etalon monitors the buildup of light at the new optical frequency. After 50 μsec the laser runs entirely in the newly selected mode; the switching time is limited by cavity dynamics.

did not switch in less than 60 μsec. This section describes the experiments that studied this slow switching, a model of the switching process that agrees with the experiments, and the difference between frequency switching of a single-frequency laser and frequency switching of a multimode laser.

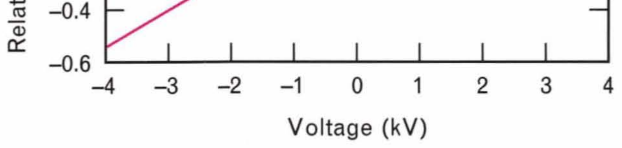


FIGURE 6. Frequency sweeping of a single-frequency laser. The laser can be frequency chirped over several free spectral ranges of the laser for times that are short compared to the mode-switching time. For a sweep time of 60 μsec, the frequency chirp is 1.1 GHz, which covers four free spectral ranges. For slower sweeps the laser mode switches.

In the initial experiments we forced mode switching by applying a square-wave voltage waveform across one of the electro-optic etalons. Figure 5 shows the square-wave voltage waveform and the laser output after passing through a fixed Fabry-Perot. The voltage step, which occurs in approximately 5 μsec, rises much faster than the frequency switches. The 5-μsec rise time for a voltage step avoids the excitation of acoustic resonances in the electro-optic tuner and damps the relaxation oscillations that result from instantaneous changes in cavity loss. The frequency switching occurs on a 60-μsec time scale; after this time 99% of the laser output appears at the new frequency.

Frequency modulating the single-frequency laser by more than one free spectral range gave further evidence for a long switching time. A 6-cm-long Brewster-cut AD*P crystal was added to the laser cavity to provide the frequency-modulation capability. The voltage control of the optical path length of the cavity had a sensitivity of 0.5 wavelengths per kilovolt.

Figure 6 shows the laser frequency, as measured with a scanning Fabry-Perot etalon, as a function of applied voltage. When the 1-kV voltage sweep took 1 msec, the laser mode hopped four times so that the laser frequency remained within one free spectral range of the frequency selected by the tuning elements. When the sweep took 60 μsec, the laser output frequency did not show mode hops but swept through 1.1 GHz linearly in the applied voltage. For sweep times between these two values we observed one, two, or three mode hops. Thus fast linear frequency modulation over several free spectral ranges can be obtained, even if the intracavity frequency filters do not track the cavity length changes. Frequency modulation of interest for coherent laser radars and coherent communications requires sweep times that are orders of magnitude shorter than 60 μsec; this topic is discussed in the next section.

Our experiments demonstrate that frequency switching of a single-frequency laser occurs on a time scale much longer than the 70-nsec lifetime for radiation in the laser cavity. The weak frequency selectivity, as shown in the right side of Figure 3(a), is the reason for the long switching time. The additional loss introduced at the original lasing frequency in the switching process is small. Because the laser continues to operate at the original frequency, which clamps the population inver-

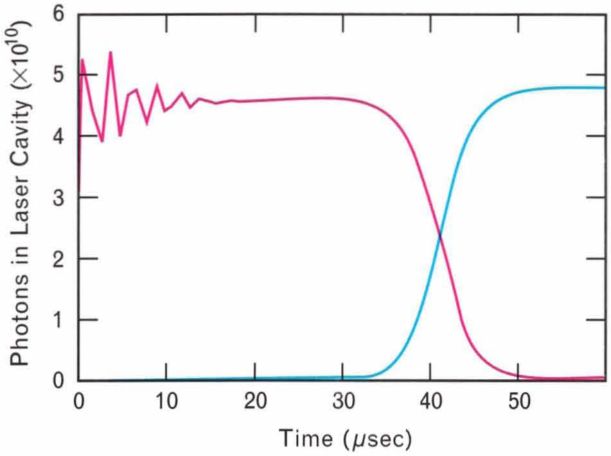


FIGURE 7. Model of the mode-hopping time for a Ti:Al_2O_3 laser. The model describes mode hopping as a slow buildup of light from spontaneous emission. Although the buildup is exponential in time, the coefficient in the exponent is small because the gain differential between the two modes is small (see Figure 3). Thus the predicted time for switching between two modes with parameters appropriate to Figure 5 is 50 μsec. The mode that was lasing prior to the frequency switch (red curve) continues to lase until the newly selected mode (blue curve) has fully turned on.

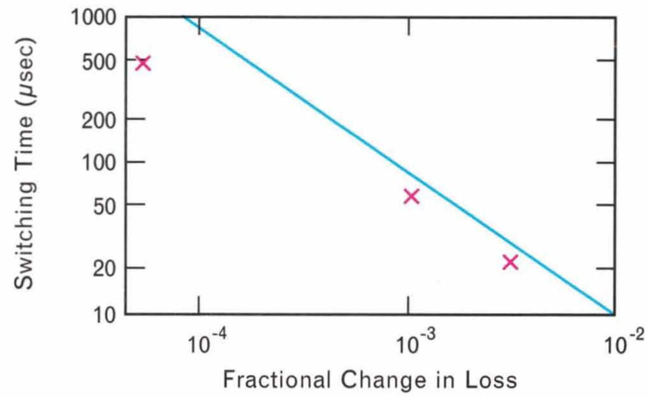


FIGURE 8. Theoretical and experimental mode-switching times as a function of loss differential. The three experimental points agree with the model, which indicates that buildup from spontaneous emission is responsible for single-frequency switching.

sion, the net gain at the newly selected frequency is small. Because of the small net gain, radiation in the new mode builds up slowly to the level that saturates the gain, and then damps the field in the old mode. This explanation suggests that the switching time should equal the cavity lifetime divided by the excess round-trip loss, which is in good agreement with the experiment.

Within the 20% experimental uncertainty, the observed switching time did not depend on whether the laser hopped in frequency by one mode spacing or by 50 mode spacings. For frequency switching by more than one mode spacing, however, we observed transient lasing in other modes as well as multimode behavior. Even though switching by more than one mode spacing has complicated dynamics, the switching time depends only on the selectivity between adjacent longitudinal modes.

To test this explanation for frequency switching while avoiding the complicated dynamics of multimode switching, we developed a two-mode model. The model assumes steady-state lasing in a single mode prior to an instantaneous change in the frequency filter. When this change occurs, the filter introduces an additional loss at the lasing frequency while decreasing the loss by the same amount at the newly selected frequency, and the newly selected frequency grows exponentially from amplified spontaneous emission. Figure 7 shows the results of numerical calculations that assume a change in round-trip loss equal to 10^{-3} due to our electro-optic etalons. The initial number of photons in the cavity at the newly selected frequency is approximately 12 [3]; this number doubles every 1.7 μsec until it starts to deplete the population inversion. After 40 μsec, saturation of gain by the newly selected frequency occurs. Our experimental results with adjacent-mode frequency switching agree well with this calculation, except that the rise of the voltage step in the experiment damped the relaxation oscillations.

In addition to illustrating the dynamics of frequency switching when only two modes are involved, the model predicts the switching time for any difference in loss. While the laser intensity and the saturation intensity only weakly affect the switching time, the cavity loss difference has a strong effect. Figure 8 compares the prediction of the model (solid line) with the experimental data from three electro-optic tuning experiments. The good agreement between the model and experiment indicates that the model accounts for the processes responsible for slow frequency switching.

In contrast, multimode standing-wave lasers can change frequency in less than 1 μsec. In fact, a laser modulated at the cavity mode-spacing frequency demonstrated wavelength switching on a time scale of 1 nsec

AGILE COHERENT LASER RADAR

LASER FREQUENCY TUNING and modulation can be important in laser radar design. A frequency-agile laser and a diffraction grating can be used for fast one-dimensional pointing without mechanical motion; the diffraction grating converts a change in laser frequency to a change in output beam direction.

In a coherent radar system the Doppler frequency shift and the range of the target can be measured simultaneously to generate a two-dimensional range-Doppler image of the target. Linear frequency modulation of the laser output provides improved images that are well suited for characterizing rotating targets [1].

Figure A shows an implementation of the agile-beam concept based on a combination of frequency tuning and mechanical scanning. In this implementation, while wavelength tuning steers the beam in the radial direction, the spinning

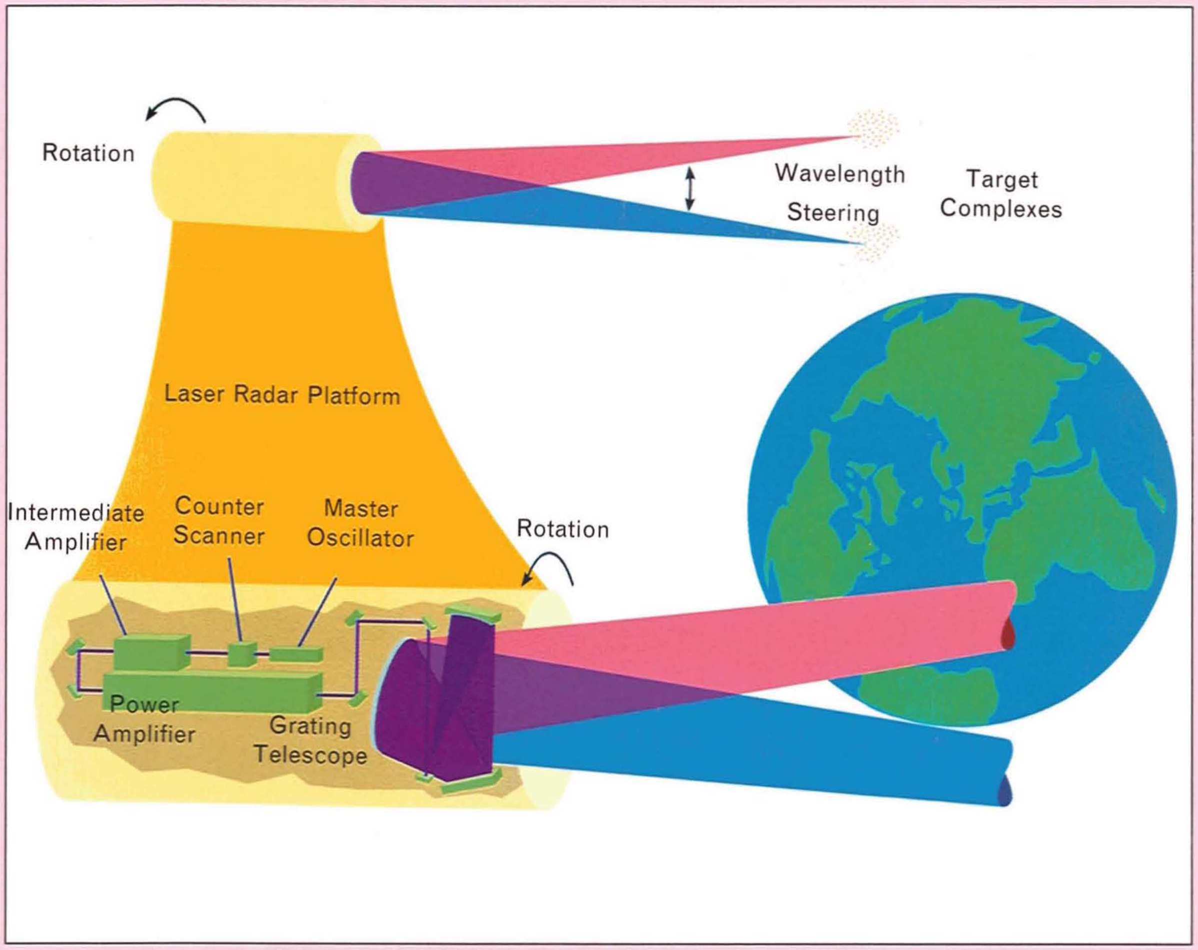


FIGURE A. Agile-beam coherent laser radar. The master oscillator is a single-frequency laser that can be tuned quickly across its bandwidth as well as frequency modulated. A counterscanner provides small angular corrections to compensate for motions such as satellite rotation. The laser amplifiers are used to produce a high-power beam necessary for long-range operation and the grating disperses the incident radiation, which allows pointing along a line by adjusting the master oscillator to the appropriate frequency.

satellite provides continuous scanning in the orthogonal direction. A counterscan against the continuous circular scan stops the beam when it finds a target. Because only small deflections are required, this counterscan is easily accomplished by an acousto-optic deflector.

With the spatial resolution provided by a 50-cm grating, each of the 2×10^5 longitudinal modes that can be accessed by a 1-m-long single-frequency $Ti:Al_2O_3$ laser points the beam in a different direction. The angular separation between adjacent longitudinal modes approximately equals the diffraction-limited far-field angle, so that mode switching can point the beam at any target.

Fast tuning within a single laser mode provides frequency modulation of the laser output. Linear frequency modulation, referred to as frequency chirp, has been used for many years to avoid high peak-power transmission in radar systems. In addition, a chirped pulse train effectively obtains high-resolution range-Doppler images without extremely high-speed electronics [1].

Reference

1. A.L. Kachelmyer, "Range-Doppler Imaging with a Laser Radar," *Lincoln Laboratory J.* **3**, 87 (1990).

[17]. Four-wave mixing in multimode lasers can generate radiation at new frequencies

$$\nu = \nu_i \pm \nu_j \mp \nu_k ,$$

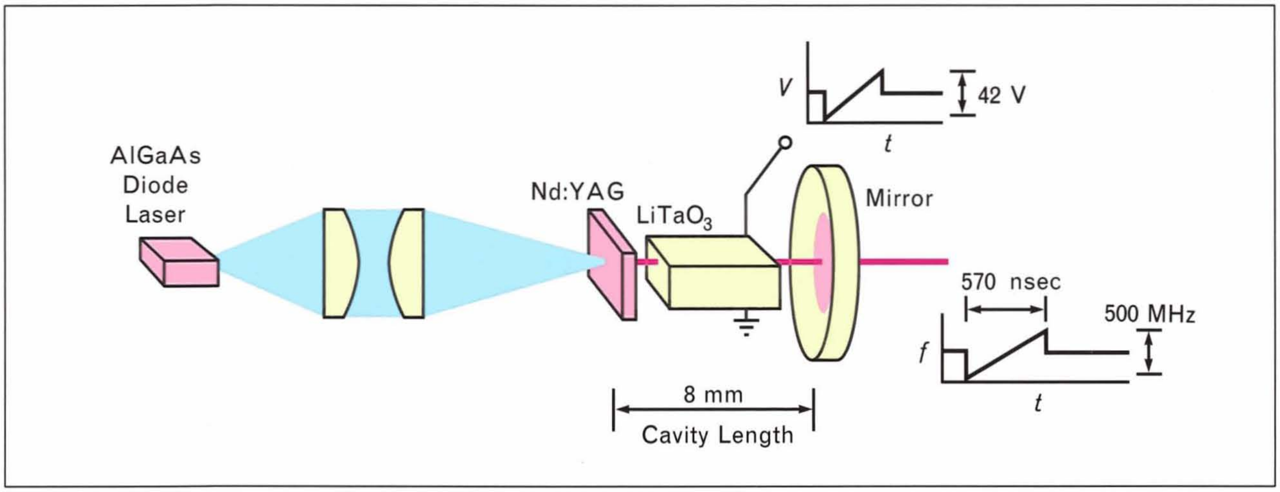
where ν_i, ν_j, and ν_k are any of the initial frequencies of the multimode laser. The field at the new frequency is seeded at a higher amplitude by four-wave mixing than by spontaneous emission, and therefore can grow more rapidly to saturation. Theory predicts that spatial hole burning present in the standing-wave laser enhances the four-wave mixing process [18].

Frequency Modulation

Although mode switching of single-frequency lasers is slow, intracavity frequency modulation can provide frequency variation to 1 GHz and above. The modulator in the laser cavity must be small to obtain high-frequency response while at the same time filling a large fraction of the laser cavity to have good voltage sensitivity. For a frequency-modulated laser to be efficient, the gain medium must be short, have a high gain per unit length, and absorb most of the pump power. Materials such as semiconductors and highly doped neodymium crystals satisfy these requirements. Diode lasers, which typically have very small cavities, are already used as frequency-modulated optical sources. Diode lasers, however, have more noise at high frequencies [19] than diode-pumped Nd:YAG lasers. In addition, diode-pumped Nd:YAG amplifiers can generate the high peak powers that are necessary for a frequency-chirped coherent laser radar (for more information see the box entitled "Agile Coherent Laser Radar").

We have constructed a compact frequency-modulated Nd:YAG laser that has frequency excursions of 1 GHz in less than 1 nsec as well as nearly linear voltage-to-frequency conversion on longer time scales. Important features include single-frequency operation, sensitive electro-optic tuning, and high-frequency modulation capability in a simply constructed yet stable cavity. The laser operates at a single frequency because the Nd:YAG crystal is thin (1 mm) and is placed at one end of the short laser cavity. A thin electro-optic modulator in the cavity yields a large frequency sweep for relatively low voltages. Damping the acoustic resonances in the electro-optic material allows nearly constant tuning sensitivity for modulation frequencies that are below, near, and above the acoustic resonances. As a result, high-frequency modulation to 1 GHz and nearly linear voltage-to-frequency conversion are obtained.

The standing-wave Nd:YAG laser (see Figure 9) is contained in a 3-cm-long stainless steel cylinder that mechanically stabilizes the laser cavity. Either a $Ti:Al_2O_3$ laser or a diode laser tuned to 809 nm, the peak of the Nd:YAG absorption band, is used to provide the pump beam. The beam passes through a dichroic coating on the Nd:YAG crystal with 80% transmission at 809 nm and 99% reflection at 1.06 μm. The laser cavity is formed by the dichroic coating on the crystal and a 5%-trans-



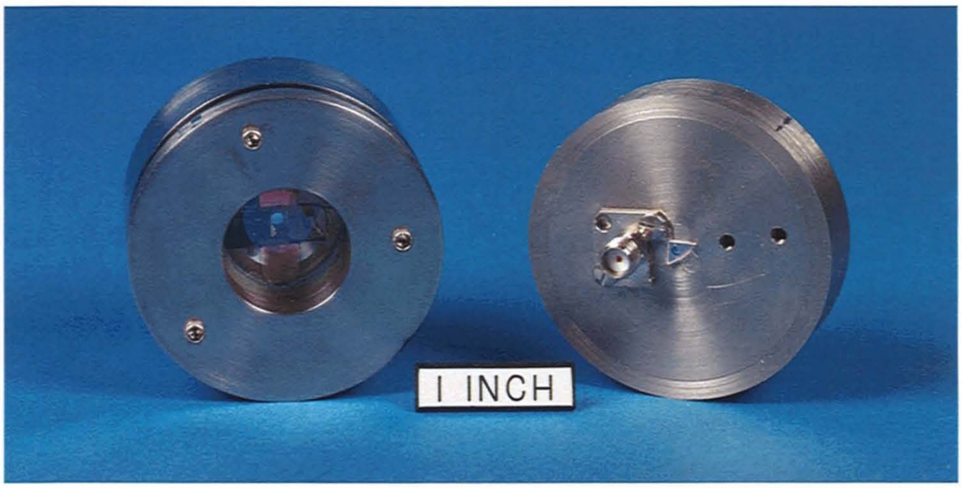


FIGURE 9. (a) Diagram of an intracavity-modulated Nd:YAG laser. (b) Photograph of the laser. The left view, taken through the output coupler, shows the optical path through the laser. The materials surrounding the optical path are used for acoustic damping of the $LiTaO_3$ crystal. The right view shows the thin Nd:YAG crystal and the connector used as a high-frequency electrical feedthrough.

mission output coupler with a 5-cm radius of curvature. All the other optical surfaces—namely, one end of the Nd:YAG and both ends of the $LiTaO_3$ modulator crystal—are antireflection coated for 1.06 μm. The $LiTaO_3$ crystal is 3 mm in length and 1 mm^2 in cross section. The 8-mm cavity length results in a mode spacing of 12 GHz.

The acoustic vibrations of the stainless steel housing result in cavity length changes on the order of 0.1 nm, which is less than an interatomic spacing, as inferred from the short-term frequency jitter of 300 kHz. For times longer than 1 sec, temperature variations in the Nd:YAG and the $LiTaO_3$ crystals limit the frequency stability. Pumping with a diode laser rather than a $Ti:Al_2O_3$ laser improves the long-term frequency stability to 10 MHz, because the diode-laser output power is more stable. Control of the temperature of the crystals or active stabilization of the laser frequency can reduce this long-term thermal drift.

The 1-mm width of the $LiTaO_3$ along the *c*-axis, across which voltage is applied, produces a 12-MHz/V tuning sensitivity, which is in agreement with the value calculated from the published coefficient [12]. The $LiTaO_3$ fills 53% of the optical path length of the cavity to provide the high tuning sensitivity. To test the frequency-sweep limit at low modulation rate, a high-voltage amplifier generated a 1-kV triangle wave at 1 kHz. The frequency swept over 12 GHz, which equals

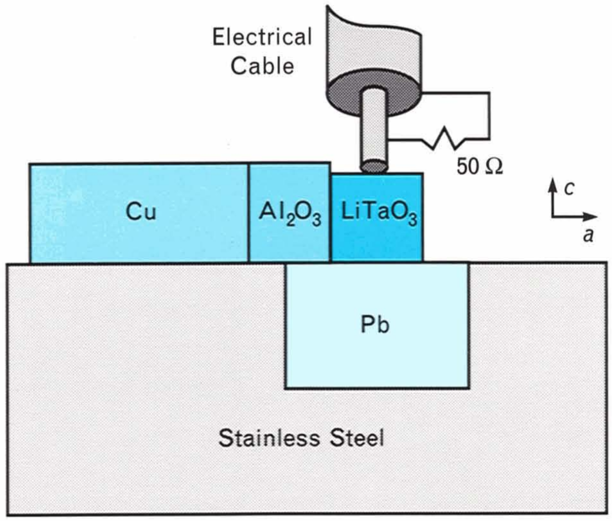


FIGURE 10. Damping acoustic resonances in a $LiTaO_3$ crystal. Because the acoustic impedance differs by a factor of 2 between the *a* and *c* axes of $LiTaO_3$, the same material cannot be used for both directions. For the *a* axis, sapphire and copper have the same acoustic impedance; for the *c* axis, lead has the same acoustic impedance.

the longitudinal-mode separation. The small size of our modulator crystal leads to low capacitance and good high-frequency response; these factors are important for extending electro-optic tuning to higher frequencies.

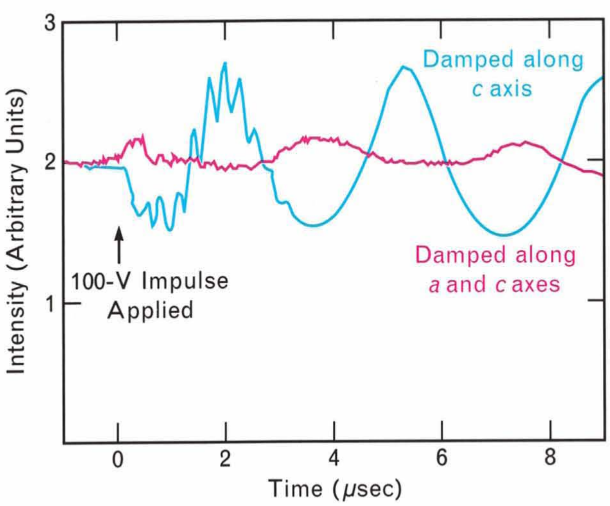
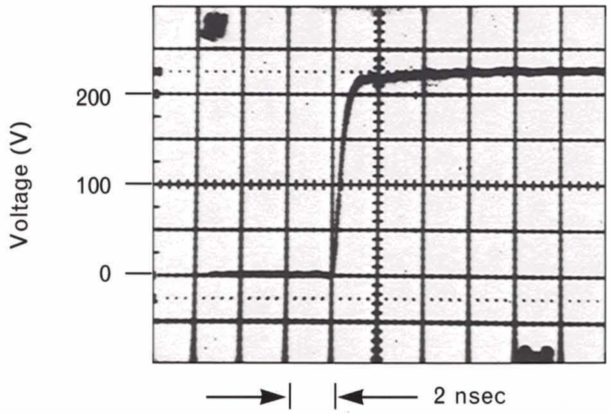


FIGURE 11. Relaxation oscillations induced by acoustic resonances. When sound waves propogating only along the *c* axis are damped, the *a*-axis waves give an acoustic resonance at 2 MHz. When damping is added for *a*-axis waves, the acoustic resonance is effectively eliminated. The relaxation oscillations are also quenched by a factor of 5.



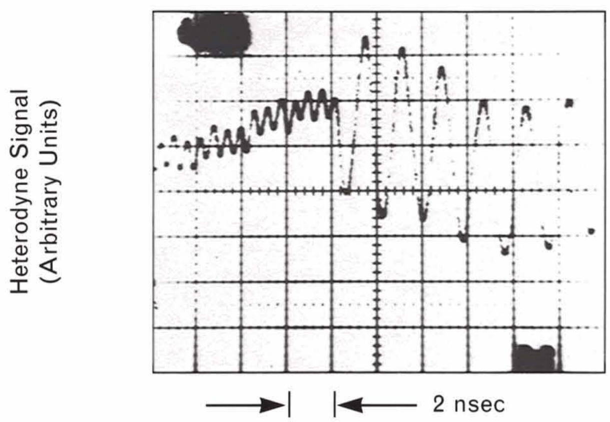


FIGURE 12. A heterodyne beat signal obtained from an applied voltage step. A 200-V voltage step causes a frequency shift of 1.2 GHz during the 0.5-nsec rise time of the step.

When the frequency of the applied voltage reaches 0.1 MHz and above, acoustic resonances in the $LiTaO_3$ cause undesired amplitude modulation and frequency modulation. To eliminate these resonances, materials that are acoustically impedance matched to $LiTaO_3$ along the *c* and *a* crystal axes are bonded to the crystal, as shown in Figure 10. These materials receive the electrically excited acoustic waves from the $LiTaO_3$. Damping of all but one acoustic mode results from bonding lead to the *c*-face of the $LiTaO_3$, as shown in Figure 11. Along the *a* axis, sapphire is bonded to the $LiTaO_3$ for its insulating properties as well as the acoustic impedance match. Sapphire, however, does not damp the acoustic wave, so these waves are further transmitted into copper, which also is impedance matched. The copper has been impregnated with polyimide to improve its acoustic damping. These techniques dampen the acoustic waves in the $LiTaO_3$ by two to three orders of magnitude,

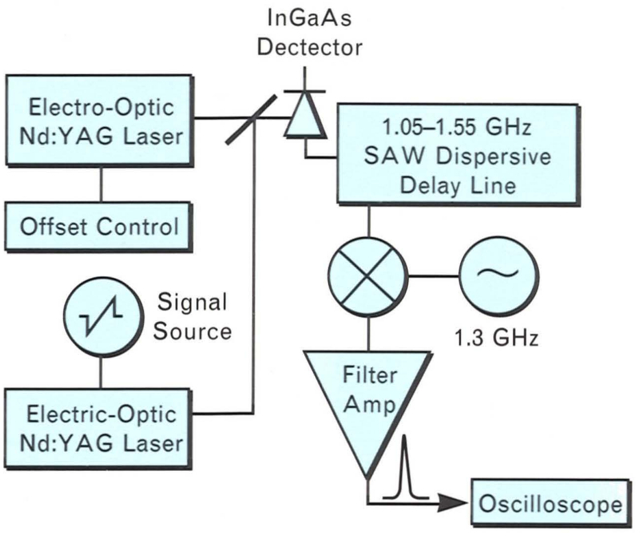


FIGURE 13. Diagram of the apparatus used to determine the linearity of frequency modulation; a similar apparatus can be used for processing a frequency-chirped coherent laser radar return. The frequency-modulated and constant-frequency Nd:YAG lasers are combined on an InGaAs detector. A surface acoustic wave (SAW) dispersive delay line is used to compress the detected beat signal. The output of the SAW device is mixed with the output of a 1.3-GHz oscillator and filtered and amplified to generate a short pulse. In a coherent radar system the time delay of the pulse can be used to determine the range of an object, while the frequency shift between outgoing and incoming signals can be used to determine the range rate.

compared to a freestanding crystal.

A 200-V voltage step with an 0.5-nsec rise time was applied to the $LiTaO_3$ to test the modulation speed of another Nd:YAG laser having a tuning sensitivity of 6 MHz/V. The output of the frequency-modulated laser and a stable single-frequency laser were combined on a 0.7-GHz InGaAs photodiode. Figure 12 shows the applied voltage step and the resulting heterodyne beat signal, as displayed on a 1-GHz oscilloscope. The heterodyne signal frequency switches from 1.75 GHz to 550 MHz. The rise time of the voltage step limits the transition time to 0.5 nsec.

When a linear voltage ramp is applied, the frequency of the laser undergoes a series of steps whose spacing in time is the cavity round-trip time. When the voltage rise time is long compared to the cavity round-trip time, the frequency has an approximate linear chirp with a fractional deviation from linearity of $t_r/2T$, where t_r is the rise time and T is the cavity round-trip time [20]. For the experimental results shown in Figure 12, the maximum nonlinearity of 15% should occur 0.5 nsec after the start of the voltage rise. Thus a stable Nd:YAG laser can be frequency modulated with good linearity up to 1 GHz. In related work, A.Z. Genack and R.G. Brewer showed that a single-step frequency change could be achieved by using a rise time for the voltage ramp that equaled the cavity round-trip time [21].

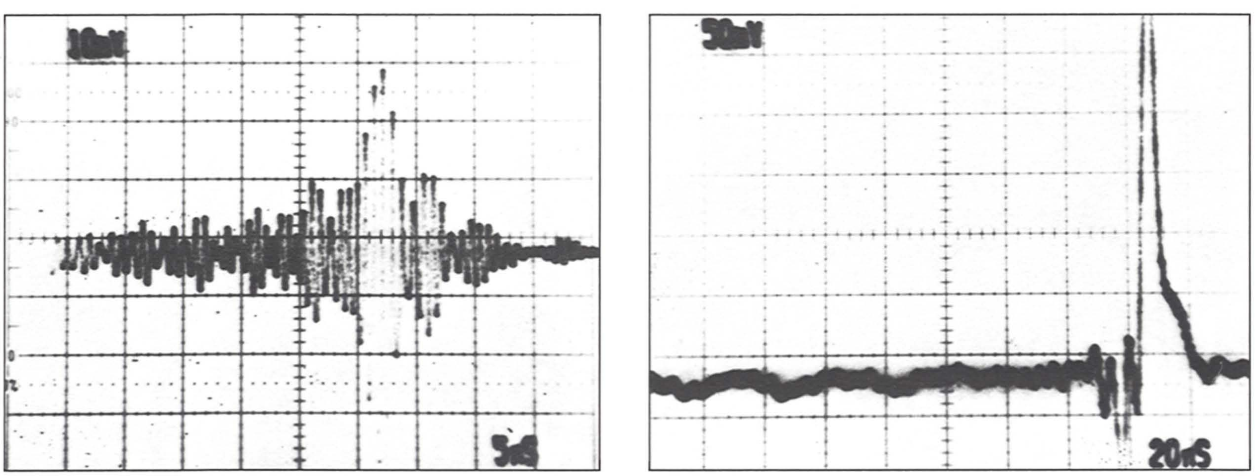


FIGURE 14. Pulse compression of a linearly chirped optical beat signal. This compressed and filtered pulse shows less than 0.4% nonlinearity for the voltage-to-optical-frequency conversion in the laser. (a) The output from the SAW device is a 1.3-GHz, 2.5-nsec pulse with numerous sidelobes. Theory predicts that the envelope for a constant intensity input pulse should be a sinc function (sin *y*/*y*). (b) The output pulse after filtering (see Figure 13) is 4 nsec wide and sidelobes are 30 dB below the main peak.

Figure 13 shows a diagram of the system used to measure the linearity of the voltage-to-frequency conversion process. A 42-V, 570-nsec linear voltage ramp was applied to the frequency-modulated laser, which generated a frequency-chirped heterodyne beat signal at the photodetector. This beat signal was compressed with a surface acoustic wave (SAW) dispersive delay line. For frequencies between 1.05 and 1.55 GHz, the SAW device delays the output relative to the input by an amount linearly proportional to the input frequency. These SAW devices have a nonlinearity of less than 0.3%. Thus a signal with a linear frequency chirp matched to the SAW device should generate a pulse whose duration is nearly the inverse of the bandwidth of the chirp. Figure 14(a) shows the SAW output signal as a 1.3-GHz, 2.5-nsec full-width at half-maximum pulse. The minimum pulse width for the 500-MHz signal bandwidth is 2 nsec, which is only slightly shorter than the observed 2.5-nsec width. Thus the nonlinearity in the voltage-to-optical-frequency conversion process is less than 0.4%, which is determined by the ratio of the 2.5-nsec pulse width to the 570-nsec chirp duration.

Further signal processing consisted of mixing the signal with a 1.3-GHz intermediate-frequency oscillator and amplifying the mixed output over a bandwidth of 0 to 100 MHz. Limiting the bandwidth increased the pulse width, but reduced noise in the wings. The resulting signal, shown in Figure 14(b), was a 4-nsec pulse with temporal sidelobes down by 30 dB; this pulse is near the 3-nsec, 40-dB sidelobe limit for a 0.5-GHz chirp with Taylor filtering [22]. The low sidelobes in the signal make such a system ideal for a coherent laser radar. In addition, the good linearity makes the frequency-modulated laser appropriate for an analog frequency-multiplexed coherent communications system.

Summary

Fast mode switching and fast frequency modulation of lasers have applications in communications and in laser radar. We have developed electro-optic devices for use with conventional tuning techniques that permit single-frequency laser operation with fast selection and control of the laser frequency. Cavity dynamics limits the time for mode switching to 60 μsec in a Ti:Al_2O_3 laser. Linear voltage-to-frequency tuning by electro-optic modulation within one mode is found to be much faster; frequency tuning of 1 GHz with a 0.5-nsec rise time has been obtained in a Nd:YAG laser.

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13. ABSTRACT *(Maximum 200 words)*

■ Electro-optic devices permit rapid wavelength selection and high-bandwidth frequency modulation in single-frequency solid state lasers. Laser dynamics limits both the speed of wavelength selection and the linearity of frequency modulation. The maximum speed of laser mode selection is determined by the buildup of oscillation from spontaneous emission. For frequency modulation, the minimum fractional deviation from chirp linearity is the ratio of the cavity round-trip time to the duration of the chirp. Nd:YAG and Ti:Al_2O_3 lasers built at Lincoln Laboratory have attained these theoretical limits.

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