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PAPER VI

Mode-hop-free electro-optically tuned diode laser

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Mode-hop-free electro-optically tuned diode laser

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A tunable external-cavity Littrow diode laser, with an intracavity electro-optical crystal, which combines a large mode-hop-free tuning range with high tuning speeds and high tuning accuracy, has been designed. A mode-hop-free single-mode tuning range of 50 GHz at 793 nm with an output power of 60 mW and tuning speeds of 1.5 GHz/μs is demonstrated. The instantaneous linewidth is smaller than 300 kHz. Generally mode-hop-free tuning is obtained when the elongation of the cavity is proportional to the cavity length measured anywhere across the beam. This elongation is achieved with an intracavity crystal in which the thickness, and thus the electric field inside it, varies across the beam. © 2002 Optical Society of America

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Over the years many applications based on the interaction between laser light and rare-earth ions doped into inorganic crystals have been proposed. For many of these applications it is important to have a single-mode laser with stable output frequency and high output power that can scan or jump fast between different frequencies over a large bandwidth with high accuracy. For example, in a recently demonstrated radio-frequency spectrum analyzer,[1] the bandwidth is ultimately set by the high-speed tuning range of the laser. Another interesting application is the quantum computer scheme that was recently suggested.[2] In this Letter a novel system that will be useful for these and other applications is described. The description of the construction begins with some general considerations that are relevant for the tuning of Littrow cavities.

A simple Littrow laser cavity can consist of a mirror, a medium that amplifies the light, and a grating that feeds back the −1st order and uses the 0th order as the output. The wavelength is roughly set by the grating, which diffracts light with a certain wavelength directly toward the mirror. The exact wavelength is determined by the standing wave formed inside the cavity. This wave has one node on the mirror surface and nodes on each groove on the grating, as indicated schematically in Fig. 1. If the parameters for the cavity are properly chosen, the cavity will oscillate at only one frequency at a time; this is referred to as single-mode oscillation.

One can tune such a laser by moving the grating. To understand fully how the frequency changes when the grating is moved, we consider the cases shown on the left-hand side of Fig. 1, each with its accompanying wavelength change on the right. If the grating is moved along the beam direction, as shown in Fig. 1(a), the standing wave inside the cavity will be stretched, leading to a continuous change in the wavelength. But as the wavelength changes, this stretching also changes the diffraction angle from the grating, since the distance between the nodes in the wave pattern inside the cavity no longer exactly matches the grating spacing measured in the direction of the incoming beam. After a while, a mode with one more half-wave ($\lambda/2$) period inside the cavity will be pointing more directly toward the mirror; i.e., the mode will have lower losses, which leads to a sudden mode hop back in frequency. If, however, the grating is moved perpendicularly to the beam, as indicated in Fig. 1(c), the distance between any particular groove on the grating and the mirror does not change. This means that, even though the cavity is becoming longer, there is no change in frequency.[3] We can, of course, also change the frequency of the laser by changing the angle of the

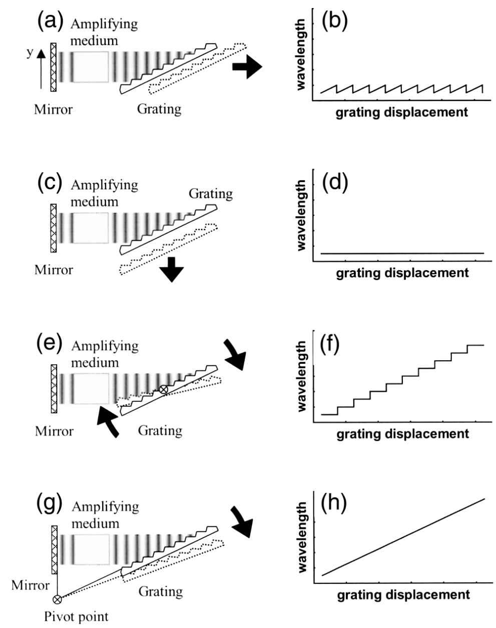

Fig. 1. (a), (c), (e), (g) different ways of moving the grating. (b), (d), (f), (h) corresponding changes in wavelength.

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238 OPTICS LETTERS / Vol. 27, No. 4 / February 15, 2002

grating, thereby choosing the wavelength fed back to the mirror. If the grating is turned around the center point of the beam, as shown in Fig. 1(e), the length of the cavity at the middle of the ray will not change. This means that there will be no change of wavelength until the next possible mode has lower losses, and then the laser mode hops to the new frequency.

So how should the grating be moved if we want to achieve continuous tuning with no mode hops? The problem with stretching the cavity, as in Fig. 1(a), is that for each groove along the grating there is one $\lambda/2$ period more in the cavity. So the elongation in the longer part of the cavity is distributed among more $\lambda/2$ periods. To achieve tuning in which the beam always is diffracted directly back toward the mirror, we should elongate all the $\lambda/2$ periods by the same amount. This condition is fulfilled if the elongation at each point is proportional to the optical length of the cavity at that point. If we assume that the optical length of the amplifying medium is equal to its physical length, we can achieve this by turning the grating around a pivot point in the position at which the mirror and grating planes intersect, as shown in Fig. 1(g). This configuration gives the smooth tuning characteristics depicted in Fig. 1(h), and lasers with this construction have been successfully tuned without mode hops over very large frequency intervals.[4]

Unfortunately, mechanical tuning is slow, and it is difficult to achieve high repetition rates, high frequency tuning speeds, and good reproducibility. To address these problems, we can, instead of moving the grating mechanically, incorporate an electro-optical crystal into the cavity. When a voltage is applied across such a crystal, the crystal experiences a change of refraction index that is proportional to the electric field, and thus a change in its optical length, which in turn tunes the laser in a manner similar to that shown in Fig. 1(a). This type of tuning can be done very rapidly,[5] but the maximum mode-hop-free tuning range is approximately equal to the mode spacing of the cavity, which is ~3 GHz for a 5-cm-long cavity.[5] Mode-hop-free tuning with an electro-optical crystal, cut as a prism that matches elongation and deflection, was recently demonstrated.[6]

Here, a novel tuning concept is presented that yields a five-times-higher frequency-change–voltage ratio and a frequency-tuning interval more than three times higher than those obtained with the prism approach. We should, however, note that the increased sensitivity is achieved mainly because the crystal is made thinner. The laser has a chirp rate of 1.5 GHz/μs and good frequency stability (see Table 1) because of its rigid monolithic aluminum design. The design is based on a Master's thesis.[7] The change in cavity length that is imposed by the electro-optical crystal the is inversely proportional to the crystal thickness. If the crystal thickness changes across the beam perpendicularly to the propagation direction, we can achieve the difference in cavity elongation that is required for mode-hop-free tuning. The proper shape of the crystal can be derived as follows: If γ is the angle of incidence on the grating and y is a coordinate as defined in Fig. 1(a), then the optical cavity length, $L(y)$, is given by $L(y) = L(0) + y \tan \gamma$.

If the height of the crystal, $h(y)$, varies slowly, then the change in the cavity length with applied voltage as a function of y is given by

$$\Delta L(y) = -\frac{a}{2} n_z{}^3 r_{33} \frac{U}{h(y)}, \tag{1}$$

where a is the length of the crystal, $n_z = n_e$ is the extraordinary refractive index, r_{33} is the relevant element of the electro-optical tensor, and U is the applied voltage.

As was concluded above, the condition for mode-hop-free tuning is that the elongation of the cavity should be proportional to the cavity length for all y. Thus we require that $\Delta L(y) = CL(y)$, where C is a constant. This means that

$$h(y) = -\frac{\frac{a}{2} n_z{}^3 r_{33} U}{[L(0) + y \tan \gamma]C} = h(0) \frac{1}{1 + \frac{\tan \gamma}{L(0)} y}. \tag{2}$$

It is easier to manufacture a crystal with flat surfaces. If the beam width is considerably smaller than the cavity length, we can, as a good approximation, linearize Eq. (2) to accommodate this condition, which yields

$$h(y) \approx h(0)\left[1 - \frac{\tan \gamma}{L(0)} y\right]. \tag{3}$$

Table 1. Summary of the Characteristics, Main Components, and Design Parameters of the Laser

Parameter or Component	Value
Single-mode tuning range	50 GHz
Frequency stability	
100 μs	300 kHz
1 ms	1 MHz
10 ms	5 MHz
Tuning response	13 MHz/V
Output power	60 mW
Maximum tuning speed	1.5 GHz/μs
Sensitivity to diode current fluctuations	20 kHz/μA
Frequency repeatability	>2 MHz after 400-MHz sweep
Laser diode	SDL-5311-G1, antireflection coated by Sacher
Lens	Geltech 350330-B; $f = 3.1$ mm
Crystal	Casix; $LiTaO_3$, $R < 0.1\%$, $r_{33} = 30.4 \times 10^{-12}$ m/V, $n_e = 2.16$
Crystal dimensions	40 mm × 15 mm × (1–1.51) mm
$\lambda/2$ plate	Casix WPF1215 for 800 nm, $R < 0.2\%$
Grating	Spectrogon L2400, Au coated, 2400 g/mm, efficiency 20% ⊥ pol. (−1st order)
γ	72.1°
$h(0)$	1.255 mm
$L(0)$	115 mm

February 15, 2002 / Vol. 27, No. 4 / OPTICS LETTERS **239**

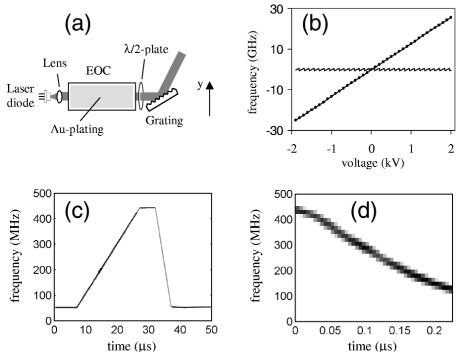

Fig. 2. (a) Schematic of the laser. The electro-optical crystal's thickness decreases in the y direction. (b) The line with the dots is a recording of a 50-GHz-wide scan. The sawtooth line shows how the tuning would have appeared with a nonangled crystal, limiting the scanning range to 1.3 GHz. (c) Recording of a 400-MHz chirp. (d) Recording of a fast scan.

Another way of deriving the required condition is by matching the change in the exit angle of the beam from the crystal caused by, in the y direction, increasing index of refraction and matching this change with the change of diffraction angle from the grating. The main characteristics and parameters of the laser are summarized in Table 1.

An antireflection-coated single-mode laser diode was used as the light source. To get as high a frequency–voltage tuning ratio as possible, it is desirable to have a thin crystal. A small beam that could pass through the thin crystal was obtained by use of a lens with a focal length of only 3.1 mm. Antireflection coating the crystal and tilting it slightly sideways prevented reflections inside the cavity. Two sides of the crystal were gold plated to form the electrodes, leaving a 1-mm frame so that electric discharges between the electrodes would be avoided. Stable single-mode operation was ensured by use of a large value of γ. Unfortunately, the diffraction efficiency for light polarized parallel to the grating's grooves is very low for large angles of incidence.[8] Therefore, we turned the polarization 90° by inserting a $\lambda/2$ plate between the crystal and the grating. The $\lambda/2$ plate was tilted 8° so that etalon effects would be avoided. The laser is shown schematically in Fig. 2(a).

The analysis of the tuning characteristics of the laser was divided into two parts. The 50-GHz continuous single-mode scanning range was checked: The voltage applied across the crystal was changed slowly while the wavelength was measured with a Burleigh WA-4500 wavemeter that had a resolution of 50 MHz. The result can be seen in Fig. 2(b). The dots on the line are the recorded measurement points, but the change was monitored continuously. The absence of mode hops was ascertained by monitoring of the smooth movement of the fringes from a scanning Fabry–Perot interferometer.

The fast scanning capabilities and short-term stability of the laser were analyzed by means of heterodyne mixing the laser with a Microlase MBR-110 Ti:sapphire laser, with a linewidth of ~100 kHz. The amplitude modulation was detected with a photodiode and recorded with an oscilloscope with a bandwidth of 500 MHz. The beat signal was analyzed with a sliding-window fast Fourier transform that gives the frequency as a function of time. The high voltage was supplied by a high-voltage amplifier (New Focus 3211). Figure 2(c) shows a recording of a 400-MHz scan; Fig. 2(d), a scan with a maximum scanning speed of 1.5 GHz/μs (see also Table 1 for the tuning characteristics). If care is taken to avoid electric discharge between the gold electrodes, it should be possible to extend the tuning range to 200 GHz or more. The tuning speed was limited by the high-voltage amplifier. If faster electronics are used, it should be possible to tune the laser much faster.

In summary, a high-speed electro-optically tunable single-mode diode laser has been designed and built. The laser was tuned without mode hops over 50 GHz. This range can readily be extended to 200 GHz. The design can, in principle, be used together with dye, solid-state, or diode lasers at any frequency at which they are available.

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