Design for a compact tunable Ti:sapphire laser

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Received July 1, 1994

Tunable laser radiation with megahertz linewidth is generated with a simple, inexpensive, and compact laser system that uses two common microscope slides as the only intracavity tuning elements. The laser emits two radiation modes whose frequencies are separated by 1.2 GHz, corresponding to the free spectral range of the laser resonator. The frequencies may be rapidly varied over a range of 1.5 GHz at a rate of 2 GHz/s.

Tunable single-mode lasers are widely used in spectroscopic, optical, and quantum-optics experiments. In the visible and near-infrared spectral ranges, dye and Ti:sapphire lasers[1,2] are commercially available, but they suffer from a complex design and tend to be rather costly. In fact, continuous tuning over several hundreds of nanometers in combination with a large scanning range requires a number of precisely manufactured intracavity elements such as birefringent filters and electronically controlled étalons. Reliable single-mode operation also demands a ring resonator geometry, which implies the use of an optical diode for unidirectional operation. To provide sufficient space for the intracavity elements, large resonators are often inevitable. This limits the free spectral range of the cavity and restricts the range and the rate at which the laser frequency may be rapidly varied. However, for many applications strict single-mode radiation is not crucial and an additional frequency component, separated for instance by several gigahertz, may often be tolerated. If one permits a second longitudinal mode, the complexity of the laser design may be drastically reduced.

In this Letter we describe a compact and low-cost dual-mode Ti:sapphire laser with two microscope cover slides as the only intracavity tuning elements. The tuning range is limited only by the spectrum of the laser mirrors, and its output frequency—consisting of two modes separated by 1.25 GHz—may be varied with a piezotranslator over a range of 1.5 GHz within 0.75 ms. The high tuning rate is particularly interesting for laser cooling of light atoms, for which the entire Doppler-broadened spectrum must be scanned within the atomic time of flight.[2] Also, the dual-mode output may in principle be exploited to enhance the conversion efficiency of a subsequent frequency-doubling stage. In addition to the second-harmonic frequency components, the sum frequency also is generated, and, if the fundamental waves are not depleted, the total converted power may exceed the yield of a single-mode frequency doubler by a factor of 1.5.[3]

The design of the laser is shown in Fig. 1. The laser consists of a 12-mm-long Ti:sapphire crystal [figure of merit >250, doping level 0.15 wt. % Ti_2O_3, absorption coefficient $\alpha = 1.6$/cm at 500 nm (Refs. 4 and 5)] with end faces cut at the Brewster angle and placed inside the focus of a symmetric standing-wave resonator. The two identical mirrors with 25-mm radii of curvature (12.6-mm diameter, 6.3-m thickness) are dielectrically coated for maximum reflectivity in the range 740–830 nm. They transmit 90% of the pump light, which is provided by an argon-ion laser (all lines, main components at 514 and 488 nm, maximum output power 9.5 W). The pump beam is focused into the crystal by a biconvex lens with a 50-mm focal length. The geometric path between the curved mirrors measured along the optical axes of the resonator is 40.4 mm, the separation between a curved and a plane mirror is 35 mm, and the incident angle on the curved mirrors is 12°. The separation between the two parallel arms is 21.5 mm. The geometry of the laser beam inside the resonator is calculated by standard techniques,[6,7] and the distance between the curved mirrors is chosen for a circular beam cross section in the focused branch of the cavity but outside the crystal. This allows for a good overlap between the laser mode and the almost circular pump beam, which is only slightly astigmatic after passing the curved mirror.

After the beams enter the crystal their cross sections are equally elliptically distorted such that the overlap between both beams is maintained. The beam waist radius (at 800 nm) inside the crystal is 40 μm in the sagittal plane and 67 μm in the tangential plane. Two additional and identical waists are located at the surfaces of the plane mirrors with the waist radii $w_s = 63$ μm (sagittal plane) and $w_t = 78$ μm (tangential plane). One of the plane

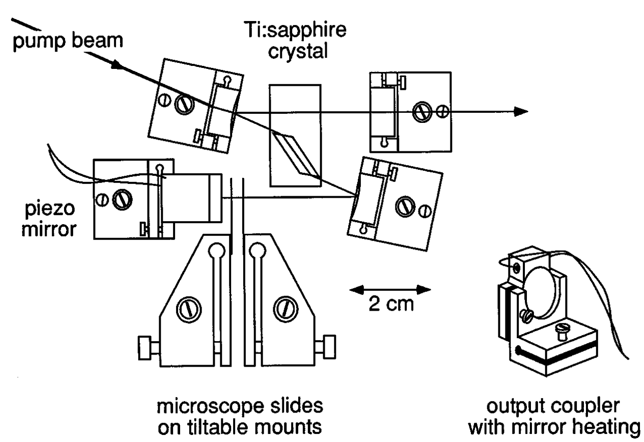

Fig. 1. Mechanical design for a compact tunable Ti:sapphire laser.

0146-9592/95/030297-03$6.00/0

mirrors (12.6-mm diameter, 3 mm thick) is coated for high reflectivity and cemented onto a piezoelectric tube (12.6-mm diameter, 12 mm long, 0.65 mm thick), which provides for fast cavity tuning. The laser light is extracted through the second plane mirror, which is dielectrically coated on a wedged substrate for 5.8% transmission at 800 nm. All mirrors are cemented onto mounts that are fabricated from a single piece of neusilber. This alloy (62% copper, 18% nickel, and 20% zinc) combines sufficient elasticity with easy machining. Horizontal and vertical angle fine adjustment is possible within a small range of 0.5° with a resolution of 0.01°. The crystal sits upon a small aluminum block (14.25 mm × 14.25 mm × 20 mm) and is held in place by heat-conducting grease. A sketch of the beam path, the crystal, and the exact position of the mirror mounts is drafted on a computer and printed with a laser printer. The actual plot paper is glued to a 20-mm-thick aluminum plate (105 mm × 120 mm), and the cavity elements are screwed to the base plate with a precision of ~0.2 mm. No fine spatial adjustment is possible or necessary. A Lucite hood efficiently reduces frequency drifts that are due to air turbulence.

Two standard microscope cover slides (Menzel, Braunschweig, Germany; thickness 0.17 mm) serve as intracavity étalons. They are adjusted to near normal incidence and may be tilted with a resolution of 1 arcsec. The wavelength is tuned by exploitation of a small thickness difference between the two étalons, as is always present within the manufacturer's tolerance. Because of the slightly different free spectral ranges, simultaneous resonance of both étalons and consequently minimum intracavity losses occur every N free spectral ranges, where $N = d_1/(d_2 - d_1)$ and d_1 and d_2 denote the thicknesses of the two étalons ($d_2 > d_1$). With a measured étalon thickness of 0.17 mm and an index of refraction of 1.5 the expected free spectral range is 0.59 THz. To separate two frequencies of minimum losses by more than 100 nm (~47 THz near 800 nm) a relative thickness difference of less than 1.3% is required. One can easily achieve this by tilting one étalon relative to the other or by selecting two étalons that by chance exhibit the desired thickness difference. Tilting one étalon tunes the laser continuously up to 20 GHz until a frequency step of ~0.6 THz occurs according to the free spectral range of the other étalon. One can achieve continuous tuning up to 10 nm by tilting both étalons synchronously. The continuous tuning range is limited by the étalon quality. Tilting the étalon also varies the lateral position of the laser spot at the étalon surface, and unwanted thickness variations may occur if the étalon is not perfectly plane parallel. However, careful adjustment of both étalons allows us to tune the laser to any wavelength between 760 and 820 nm. We have also operated the laser with a mirror set optimized for 972 nm and found a tuning range of 956–1010 nm. To preselect the operating wavelength of the laser, we chose the dielectric coating of the output coupler such that its transmission spectrum partly compensates for the gain curve of the Ti:sapphire crystal. At 972 nm the mirror coating transmits 3.5%.

Near 800 nm the laser reaches threshold at 0.9 W of pump power incident upon the cavity mirror (Fig. 2). The slope efficiency of 32% results in an output power of 2.6 W at 9 W of pump power. Near 980 nm the laser threshold is 3.4 W. The output power increases with pump power at a rate of 12% and reaches a value of 750 mW at 9 W of pump power. If the glass plate étalons are removed from the cavity the output at 980 nm is slightly improved (2.8-W threshold, 16% slope efficiency), whereas at 800 nm without étalons the laser threshold decreases by only less than 10%. At 980 nm the small-signal gain of the crystal apparently depends on temperature; after several minutes of operation the heat produced inside the crystal degrades the laser performance. A modified crystal mount with a integrated water cooling eliminates this problem. At 800 nm the water cooling has no effect.

Stable dual-mode operation (Fig. 3) is obtained if the wedged output coupler is replaced by a mirror upon a plane-parallel substrate (12.6-mm diameter, 6.3 mm thick) such that an additional étalon is formed between the high-reflecting surface and

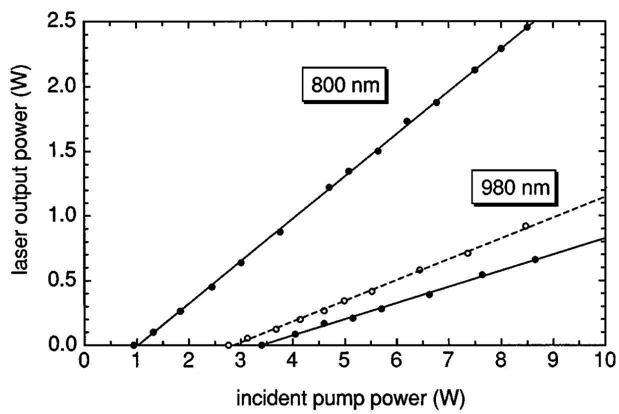

Fig. 2. Laser output versus pump power incident upon the curved resonator mirror. The dashed line describes the laser at 980 nm when the glass plate étalons are removed from the cavity.

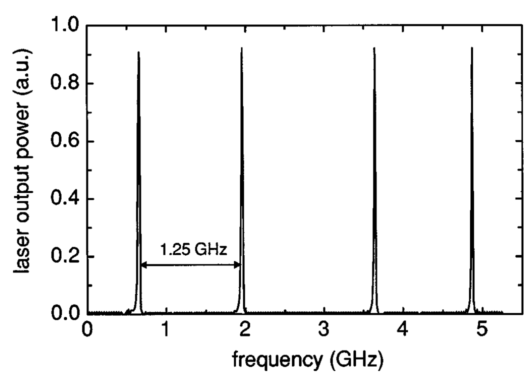

Fig. 3. Laser output spectrum recorded with a Fabry–Perot spectrum analyzer (free spectral range 3 GHz). The two modes are separated by the free spectral range of the laser cavity (1.25 GHz). The observed linewidth of 3 MHz is limited by the resolution of the spectrum analyzer.

the second uncoated surface. The transmission of the output coupler is therefore frequency dependent with a periodicity of 16 GHz and a minimum (maximum) transmission of 5% (10%). This is sufficient to suppress all longitudinal modes but two. Because of spatial hole burning, the two remaining modes acquire their gain from different regions inside the crystal, and it is difficult to suppress one of the two modes with a frequency-selective element. The frequency of both modes may be scanned by means of the piezomirror at a rate of ~2 GHz/s. The tuning range in which the power of one of the two modes stays constant is 1.5 GHz. At the edges of this range one mode is reduced in intensity, and a third longitudinal mode appears at the opposite side of the central mode. The center of the scanning range is determined by the spectrum of the output coupler étalon and its frequency of minimum transmission. To adjust this frequency we control the temperature of the output coupler with a small heating resistor (Fig. 1) and an electronic servo loop. The small temperature sensitivity of ~1 GHz/K imposes no special requirements on the quality of the stabilization electronics; the temperature of the mirror must be kept constant only to within 0.1 K.

We have carried out some tests with coated glass plate étalons (10%, 19%, and 30% reflection at each surface). Single-mode operation has not been obtained this way; the scanning range is, however, enhanced to ~2.3 GHz if one of the two étalons is coated with a single quarter-wave layer on both sides (10% reflection at 800 nm). Coatings with higher reflection reduce the laser power as a result of multiple reflections inside the étalon that guide the light outside the laser mode.

We have presented a novel design for a compact tunable Ti:sapphire laser. The wavelength is adjusted with two intracavity étalons, which are simple microscope cover slides. The laser frequency spectrum consists of two longitudinal modes separated by 1.25 GHz. Both modes may be rapidly tuned over 1.5 GHz at a rate of 2 GHz/s. A maximum output power of 2.6 W at 800 nm has been achieved. The laser may find its application in a large number of spectroscopic and optical experiments for which until now only expensive commercial single-mode lasers have been available. Because of its large scanning speed and its high-output power, the laser is particularly advantageous for optical cooling experiments and to pump frequency-doubling stages.[8]

This research has been partially supported by the Deutsche Forschungs Gemeinschaft and by the European Community (grant HCM CT. 930105).

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