Near-IR tunable laser with an integrated LiTaO₃ electro-optic deflector

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We report the successful demonstration of a near-IR tunable laser (1525.4–1558.2 nm) that uses an integrated LiTaO₃ deflector in combination with a reflection grating as an electronically tunable filter. The electro-optic deflector is a unique integrated optical device and consists of a horn-shaped array of electro-optic prisms in series. The almost 33 nm of tuning covers a wavelength region of high interest to the communications industry (1527–1550 nm). © 2002 Optical Society of America


1. Introduction

Rapidly tunable lasers are in great demand for wavelength division multiplexed optical communications because of the need to transport information over multiple wavelength channels on a single fiber. The lasers need to be reliable and low in cost. These lasers can either be used as spares for fixed-wavelength lasers in case of failure, as tunable sources in advanced wavelength-routed optical networks, or as high-performance lasers for component testing and characterization. There is also a need for such rapidly tunable lasers in IR spectroscopy and for detection of toxic chemicals. A tuning mechanism that is nonmechanical, electronically tuned, and has the potential to quickly scan accurately and repeatably over a wavelength range would be desirable.

One popular approach to tunable laser design involves use of a gain medium in an external-cavity architecture with wavelength tunability provided by an intracavity tunable filter. Most current tunable filter designs have moving parts such as motor-driven rotatable mirrors,¹ prisms or reflection gratings,² or piezoelectrically tunable fiber Fabry–Perot filters,³ although nonmechanical filters such as acousto-optic deflectors⁴ have also been demonstrated. However, most of these approaches¹–³ suffer from backlash and hysteresis and do not have the advantages of the electronic tunability of the laser presented here, whereas acousto-optic deflectors⁴ normally require high rf drive powers and are difficult to design with narrow (<1 nm) passbands. A nonmechanical tuning mechanism, such as electro-optic tuning, that allows rapid, accurate, and reproducible wavelength tuning is highly desirable.

We report the successful demonstration of a near-IR tunable laser (1525.4–1558.2 nm) that uses an electro-optic tuning mechanism based on a new tunable filter by use of an integrated LiTaO₃ deflector in combination with a reflection grating. The electro-optic deflector design⁵ is based on a series of inverted prism domains of monotonically increasing dimensions in a horn-shaped geometry for maximum angular deflection range, in contrast with a rectangular geometry based on a series of equally sized inverted prism domains⁶ (Fig. 1). The 15-mm-long, 286-µm-wide horn-shaped deflector, designed in such a way that each successive prism is just wide enough to accommodate the deflected beam, is capable of a deflection of 27.2 mrad/kV at 1558 nm.⁷ For a rectangular deflector and horn-shaped deflectors of equal length and comparable widths, a higher voltage can be applied to the horn-shaped deflector than the rectangular deflector, before the beam is deflected out of the side of the device. We chose to implement our deflectors in LiTaO₃ because the near-constant domain-wall velocities during the poling of these
crystals provide greater control of prism dimensions, making it easier to fabricate these devices with high yield. Although LiNbO\(_3\) has a slightly higher index of refraction and larger electro-optic coefficients than LiTaO\(_3\), the relatively jerky domain-wall motion during poling of LiNbO\(_3\) makes it more difficult to implement optimized horn-shaped deflector geometries in this material. Subsequent to the experiments described here, we became aware of a recent conference proceeding in which a 780-nm laser diode was tuned with an electro-optic deflector by use of a tuning concept similar to that reported here. However, because LiNbO\(_3\) was used, the deflector design was implemented in a rectangular geometry and, as discussed above, resulted in an electronic tuning range of only 1 nm, in contrast to the nearly 33 nm of tuning presented here with the horn-shaped scanner design.

2. Experimental Setup

The schematic diagram of the near-IR tunable laser is shown in Fig. 2. The gain medium used was a 980-nm diode-pumped Er:SiO\(_2\) fiber. The laser cavity was formed by a gold-coated fiber tip at one end of the cavity and an external gold-coated reflection grating (600 grooves/mm, 28° 41′ blaze at 1500 nm, 78% efficiency) positioned after a collimating lens. The fiber facing the scanner and grating was angle polished to avoid lasing off that end, and a 20× microscope objective was used to collimate the fiber output. A 75-mm focal-length lens was used to focus the collimated beam into the electro-optic deflector, whereas an 84-mm focal-length aplanat lens was used to near collimate the output beam from the deflector onto the fixed grating. Applying a voltage to the device deflects the light beam and consequently changes the angle of incidence onto the grating. The wavelength-dependent angular sensitivity, combined with the angular deflection from the electro-optic deflector, acts as the wavelength tuning mechanism. A maximum applied voltage of 4.3 kV (15.9 kV/mm) was used to remain well below the coercive field of 21 kV/mm used to create the domains in the deflector. It was necessary to tilt the deflector slightly to avoid lasing off the front face of the crystal.

3. Results and Discussion

A. Passband

The grating filter passband \(\Delta \lambda\) is determined by \(\Delta \lambda = \lambda / N\), where \(\lambda\) is the wavelength of the laser and \(N\) is the number of grooves illuminated on the 600-groove/mm grating. The laser intracavity beam, incident on the grating, was measured to be 1.1 mm in diameter, resulting in an estimated passband of \(\sim 2.5\) nm. This calculation is in agreement with the measured passband of \(2.4 \pm 0.1\) nm.

B. Laser Results

Figure 3 illustrates the 32.8-nm scanning range that we observed with this laser when the applied voltage was tuned from \(-1.5\) to 4.0 kV. The wavelength of the laser was a linear function of the applied voltage \((5.9\) nm/kV). The accuracy of the wavelength selection is dependent only on the accuracy of the voltage source. Figure 4 shows a set of spectra with a slightly less optimum deflector alignment than the previous set, showing a total tuning range of 31.9 nm and a 5.3-nm/kV tuning efficiency. Tuning gaps at \(-1.5\) and \(-0.5\) kV were observed. The power loss as the beam propagated through the ferroelectric crystal at these voltages was probably too high for lasing to occur. The loss was likely a result of the laser being...
misaligned with the ferroelectric domains and scattering occurring at the domain walls. The laser could be tuned over its entire range by more careful alignment of the laser with the ferroelectric domains. With a pump power of 150 mW, the laser power was 200 μW at a wavelength of 1558 nm. The ratio of the peak power to the background ranges from ~15.5 to almost 30 dB. For most of the wavelength range, the ratio is greater than 20 dB, which is sufficient for many laser applications. However, the ratio of the peak power to the peak (at 1534 nm) of the amplified spontaneous emission varies from a low of 2 dB to a maximum of 19.5 dB, with the majority well above 10 dB. The resolution bandwidth of the optical spectrum analyzer was 0.1 nm, whereas the laser linewidth is 2.4 nm. The amplified spontaneous emission peak can be suppressed by the addition of an external or intracavity gain-flattening filter.

C. Optimum Lens Position

The intracavity beam’s angle of incidence onto the grating determines the wavelength supported in the laser cavity.9 Ideally, the beam must be collimated to ensure good coupling of the reflected light back into the fiber. However, to the first order, if the beam is perfectly collimated, angular deflection at the scanner will merely be translated into linear displacement as the beam exits the aplanat lens, resulting in zero tuning efficiencies. Therefore, in the present laser embodiment, a design trade-off exists between the filter’s tuning efficiency and effective insertion losses. To find the optimum lens position, we varied the tuning efficiency from 5 to ~4.3 kV/nm by moving the lens from ~11 to 5 mm, where the origin corresponds to the aplanat lens positioned one focal length from the focused beam waist inside the LiTaO3 deflector. These tuning efficiencies were found to be consistent with first-order estimates based on a simple model.9

4. Future Directions

There are several key improvements that could be made to the laser to increase its tunable range, narrow the passband, or make it more compact. One such improvement would be to antireflection coat the crystal faces to allow the deflector to be perfectly aligned with the output of the fiber laser, enabling use of the full deflection range of the device (27.2 mrad/kV),7 corresponding to an improvement of 50%. With filter linewidths estimated to be 2.5 nm, the laser was expected to have a multimode emission over a ~0.25-nm spectral range. Note that the focus of these experiments was on the demonstration of an effective electronic tuning mechanism for tunable near-IR fiber lasers and not on the generation of narrowlinewidth emission. However, future tunable lasers can be designed for single-frequency operation by use of denser grating grooves, grazing incidence (Littman–Metcalf configuration10) geometries, appropriately designed secondary filters (e.g., high-finesse etalons), or linewidth-narrowing devices (e.g., wavelength-tracking saturable absorbers11). The tunable laser can be made more compact by use of gain media with significant gain anisotropy (e.g., quantum-well semiconducting materials or rare-earth-doped polarization-maintaining fibers) and rotated to match the crystal’s optimum polarization orientation to eliminate the intracavity polarizer and by use of a device with a collimating electro-optic lens train and a horn-shaped deflector prism train integrated in a single device, similar to one such electro-optic element that we have previously reported,12 eliminating two intracavity lenses. Although the current design of the tunable laser requires kilovolt voltages, by using thinner devices (of the order of tens of micrometers rather than hundreds) or using materials with higher electro-optic coefficients, we could reduce the applied voltages to a more reasonable tens of volts. We can also make the laser more versatile by using gain media that emit at different spectral ranges. Future tunable lasers can also be designed to emit at different spectral ranges within the optical transmission window of LiTaO3 (0.4–5 μm). Experiments are currently in progress to demonstrate a tunable mid-infrared (3-μm) fiber laser with diode-pumped Er:ZBLAN fibers.13

5. Conclusion

We have demonstrated purely electronic wavelength tuning of a near-IR laser that incorporates an electro-optic deflector, eliminating the need for a motor-driven grating. The design resulted in ~33-nm electronic tuning range that exceeds that of the previously reported (~1-nm electronic tuning ranges), similarly designed visible laser.6 Because the electro-optic effect is a virtually instantaneous nonlinear optical phenomenon, the device speeds are limited only by the electrode design (i.e., drive and input impedance matching, optical and rf driving field coincidence—traveling-wave design issues), and the switching times can be in time scales of nanoseconds to picoseconds, allowing the potential for use in a large number of applications in which both wavelength tunability and tuning speed are important, such as in reconfigurable wavelength division multiplexing sources14 or spectroscopic uses15 such as differential absorption lidar.
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References