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There has recently been rapid development of monolithic microchip lasers, mostly based on Nd:YAG or Nd:YVO4 crystals.1 Passively Q-switched monolithic chips, pumped by cw IR diodes generate subnanosecond pulses at 1064 or 532 nm with microjoule energies, resulting in peak powers of tens of kilowatts. Such commercially available lasers are robust and reliable, owing to their monolithic construction, which also enables simple mass production, resulting in low unit cost.

Microchip lasers have employed a range of alternative laser crystals, such as Tm:YVO4 (Ref. 2), Cr:LiSAF,3 Yb:YAG,4 Cr:YAG.5 While some of these crystals are capable of lasing over a broad wavelength range, the microchip cavity structure does not lend itself to standard tuning techniques, such as birefringent tuning or etalon tuning; these techniques rely on the rotation of the tuning element relative to the optical path to achieve tuning and so cannot be applied to a monolithic laser design. Coupled-cavity designs have been used to achieve broad tunability,3 while maintaining a monolithic structure, or alternatively miniaturized conventional laser architectures may be used that maintain the advantage of a short cavity but lose the key advantages of ease of mass production, simplicity, and robustness.6

In this Letter we propose a monolithic tunable laser where a wedged etalon is used as a tuning element. The wavelength transmitted through a wedged etalon is changed by translating rather than rotating the etalon. By employing a wedged etalon in a miniature or monolithic cavity that uses plane cavity mirrors, the laser can be broadly tuned by translating the entire cavity relative to the pump beam. Using this design will permit widely tunable lasers to benefit from all the advantages of the monolithic microchip architecture.

Wedged etalons7–9 (also known as interference wedges or Fizeau interferometers) have been used for many years as tuning elements for the coarse tuning of broadly tunable lasers and were frequently used in early commercial dye lasers (e.g., SpectraPhysics 375-50). A wedged etalon is simply an etalon whose mirrors are mounted at a small angle to one another. For such an etalon, the set of transmission wavelengths varies according to the thickness of the part of the etalon sampled by the beam, and so a laser can be tuned by translating the wedged etalon perpendicular to the cavity axis.

As a particularly demanding example of wedged etalon design and performance, we consider tuning a Ti:sapphire laser from $\lambda=750$ to $850$ nm by translating an air-spaced wedge etalon by 2 mm. For a free spectral range of 100 nm for wavelengths around 800 nm, we require a spacing $t$ of less than 3.2 $\mu$m; a suitable etalon would be 2.625 $\mu$m thick, increasing in thickness to 2.975 $\mu$m over 2 mm. This corresponds to a wedge angle $\theta=1.75 \times 10^{-4}$ rad. Operating in seventh order (i.e., $t=7\lambda/2$), this etalon will act as a transmission filter with the peak transmission wavelength varying from 750 to 850 nm as it is translated laterally by 2 mm. Note that the etalon must be mounted in the laser cavity at a small fixed angle $\alpha$ to the optical axis (e.g., 0.5°) so that the reflected, rejected wavelengths are removed from the cavity mode.

The performance of a wedged etalon can closely approach that of a standard Fabry–Perot etalon and has been analyzed previously.8 There are three differences to consider. First, unlike a Fabry–Perot etalon, the peak transmission $T_{\text{max}}$ of an ideal wedge etalon is less than 100%. For a Fabry–Perot etalon, the family of contributing beams that constitute the output beam, each undergoing a different number of round trips inside the etalon cavity, interfere exactly in phase, resulting in $T_{\text{max}}=100%$. This is not the case for a wedged etalon. A phase error $\varphi=8m^3\vartheta t/3\lambda$ accumulates with increasing number $n$ of round trips, leading to imperfect interference and a reduction in $T_{\text{max}}$. This reduction depends strongly on the etalon mirror reflectivities $R$ and can be calculated numerically; for the Ti:sapphire etalon discussed above, $T_{\text{max}}=99.9\%$ for $R=95\%$. We conclude that for etalons considered here we may disregard this effect.

A second consideration concerns lateral displacement of contributing beams emerging from the etalon. For a spatially narrow incident beam, lateral displacement of successive beams can lead to a decrease in $T_{\text{max}}$. Since etalons in laser cavities must be tilted relative to the cavity axis, even Fabry–Perot etalons exhibit such walk-off.10 While walk-off loss is en-
hanced in wedged etalons, in the case under consideration the additional walk-off is negligible. The walk-off distance $\delta$ for the $n$th contributing beam is given by $\delta=2nta$. The effect on the etalon transmission can be calculated numerically. Considering the etalon above at an angle of $\alpha=10^{-2}$ rad probed by a beam with a spot size of 60 $\mu$m, we calculate $T_{\text{max}}=98.5\%$ for $R=90\%$ and $T_{\text{max}}=99.5\%$ for $R=70\%$.

A final consideration is the width in space of the transmission maxima for a given wavelength. A monochromatic beam passing through a wedged etalon placed for maximum transmission on the beam axis will experience an attenuation of the beam wings. The magnitude of this loss depends on the wedge angle, beam width, and etalon mirror reflectivities. For the etalon above, and for a beam with a spot size of 60 $\mu$m, we calculate $T_{\text{max}}=86\%$ for $R=90\%$ and $T_{\text{max}}=98\%$ for $R=70\%$. This loss for a given etalon can be reduced as required by decreasing the mode size at the etalon.

From this discussion we can conclude that of the three causes of loss, the phase error may be entirely neglected, and attenuation of the beam wings dominates, with the losses increasing with increasing etalon reflectivity. We should select the etalon with the highest reflectivity consistent with acceptable losses; this maximizes the finesse that in turn decreases the linewidth of the tuned laser output and ensures that laser action is forced at the wavelength of maximum etalon transmission.

We have conducted experiments by using miniature cavities to demonstrate the potential of the wedged etalon for microchip laser design. For the following experiments we have used Ce:LiCAF as a laser material. This is a material that when pumped with 266 nm pulses emits laser radiation directly in the UV and is tunable from 282–314 nm.11 The design process above for an etalon to tune a Ti:sapphire laser can be applied to the Ce laser in the same way, and it is found that the design restrictions are considerably eased. For full tuning over 32 nm, a suitable etalon has a spacing of 1.3 $\mu$m decreasing to 1.1 $\mu$m over a length of 2 mm. This is a smaller wedge angle and a smaller separation than the wedge considered above for a Ti:sapphire laser; walk-off loss will be reduced, leaving attenuation of the beam wings as the dominant loss mechanism, and we can expect less than 1% transmission loss for a beam with a 60 $\mu$m spot size through such an etalon with $R=70\%$.

Figure 1(a) shows the miniature cavity used in these experiments. The pump laser pulses were derived from a 532 nm microchip Nd:YVO$_4$ laser (Alphalas GmbH) running at a repetition rate of 1 kHz, which was frequency doubled by using a $\beta$-barium borate crystal. The resulting 266 nm pulses had an energy of up to 12 $\mu$J and a pulse duration of 0.8 ns. The 5 mm long laser cavity consisted of a plane input coupler mirror (93% transmission at 266 nm, >99% reflectivity at 285–340 nm) and a plane 90% reflectivity output coupler. The pump beam was focused to a spot size of 60 $\mu$m. The laser crystal was a square-cut Ce, Na:LiCAF crystal with a Ce doping of 3.5% in the melt. The uncoated 2.2 mm long crystal had its $c$ axis in the plane of the end face and was aligned with the $c$ axis parallel to the polarization axis of the pump beam ($\pi$ polarization configuration). Single-pass absorption of the pump radiation was 88%.

A suitable wedged etalon was constructed from two 1 mm thick fused silica plates, each with a $R=70\%$ dielectric coating on one face and a broadband anti-reflection coating on the other. The plates were placed with the reflecting faces in contact; this generally resulted in a wedged air gap between the plates of approximately the correct separation and wedge angle. The wedge angle and plate separation were diagnosed by using a sodium lamp to directly view the wedge fringes, along with a broadband source and a spectrometer to measure the reflected spectrum. The plates were then manipulated until the desired wedge was achieved and bonded in place.

Figure 2 shows the output of the Ce laser cavity as a function of tuned wavelength set by translating the whole laser (cavity mirrors, laser crystal, and wedged

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**Fig. 1.** (a) Miniature embodiment of a translation-tuned laser. The plane–plane cavity contains the laser crystal and an etalon constructed from two dielectric-coated plates mounted at small angle. (b) Monolithic laser, which could be manufactured by coating an etalon structure, including a wedged spacer layer, directly onto one of the substrates.

**Fig. 2.** Tuning curve for the translation-tuned Ce:LiCAF laser.
etalon as a unit) perpendicular to the pump beam. Full tuning across the range of Ce:LiCAF was observed from 282 to 314 nm, with a peak output power of just over 1 mW at 288 nm. The linewidth of the output was approximately 1 nm across the entire tuning range. Figure 3 shows how the position of the etalon and laser cavity (relative to the pump beam, measured with an arbitrary zero) determines the running wavelength of the laser; the output wavelength tunes approximately linearly with translation. The wavelength jumps at either end of the tuning range are caused by different transmission orders of the etalon’s becoming coincident with the laser tuning range. If the free spectral range of the etalon is too small, this jumping prevents full tuning to the wings of the tuning curve. The spacing of the etalon as a function of position can be calculated from the data in Fig. 3. Plotted lines in Fig. 3 show the deduced locations of the peak of the seventh-, eighth-, and ninth-order transmissions as a function of cavity position. Thus the etalon thickness for cavity positions between 10 and 13 mm decreases from 1.265 to 1.085 \( \mu \text{m} \) (Fig. 3, right axis), corresponding to an etalon wedge angle of \( 6 \times 10^{-5} \) rad.

The efficiency of the laser operation, approximately 9% at the peak of the tuning curve, is low for a tunable Ce:LiCAF laser, which typically achieves 25–30% efficiency. The low efficiency was found to be due to losses induced by the wedge etalon. Using the 266 nm pump beam focused to the same spot size as the cavity mode through the etalon, we measured the transmission of the etalon as a function of position. The transmission closely follows the expected etalon transmission curve, with a peak transmission of 91%, a minimum transmission of 8%, and a finesse of 6. The low peak transmission results in an 18% round trip loss; since this is large in comparison with the 10% output coupler transmission, the laser efficiency is poor. For this wedge, we expect a theoretical peak transmission of greater than 98%; the remaining dominant loss we attribute to poor antireflection coatings on the outer surfaces of the etalon and losses due to contaminants on the etalon reflective surfaces. Both of these problems would be removed by moving to a solid dielectric etalon design.

The proposed laser architecture, where tuning is accomplished by translating the entire laser as a block, can be applied to monolithic lasers, in which the entire laser is bonded as a single unit. Figure 1(b) shows one possible design for such a monolithic tunable laser. In this design the etalon is dielectric spaced, with the spacer layer being wedged; such wedged layers are commercially produced.\(^\text{12}\) We believe that this design will offer all the advantages of robustness, stability, and ease of manufacture enjoyed by microchip lasers to a new range of broadly tunable laser systems.

In summary, the use of a wedged etalon allows lasers to be tuned by translating the etalon rather than rotating an element as is the case for birefringent tuners or conventional etalons. For plane–plane laser cavities containing a wedged etalon, this approach can be taken one step further, with tuning achieved by translating the entire laser. By replacing air-spaced etalons with wedged solid dielectric etalons, the laser cavity can be substantially simplified and even built as one monolithic block, bringing significant advantages of robustness and reliability. This architecture is applicable to a range of tunable solid-state lasers, and we have demonstrated the technique for a Ce:LiCAF laser, showing full tuning from 282 to 314 nm.

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References