Application of amorphous silicon subwavelength gratings in polarization switching vertical-cavity surface-emitting lasers

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Amorphous silicon subwavelength gratings have been fabricated. Their use as quarter-wave plates in polarization switching vertical-cavity surface-emitting lasers with tunable oscillation frequency as high as several terahertz is proposed. The substantial increase in frequency comes from a reduction in the oscillator cavity length due to the small thickness of the grating (only about one-third of the wavelength thick). The frequency tuning is provided by fabricating the wave plate and a partial reflector monolithically on a movable microcantilever. *© 1997 American Vacuum Society.* [S0734-211X(97)17806-4]

I. INTRODUCTION

The generation of ultrahigh frequency laser pulses is very useful in many areas of science and engineering. For instance, ultrahigh frequency lasers are greatly needed as the light sources for ultrahigh data rate telecommunication. An ultrahigh frequency laser, together with a high-speed photodetector, can form a tunable millimeter wave generator that has an unprecedented miniature size and high efficiency. They also can be used as clocks. Furthermore, the fast lasers are the key element in electro-optical sampling, which can be used for remote sensing, characterization of high-speed electronics, understanding of transport in nanostructures, and chemical reactions.

There are two approaches in the direct generation of high-frequency laser pulses: gain switching and mode locking. The frequency in the gain switching method is intrinsically limited by the carrier relaxation frequency.[1] The frequency in the mode-locking method is determined by the laser cavity length. Currently, the highest frequency demonstrated is 130 GHz for gain switching lasers[2] and 350 GHz for mode-locked lasers;[3] both using edge emitting lasers.

Vertical-cavity surface-emitting lasers (VCSELs) have many advantages over edge emitting lasers, such as the ability to form two dimensional arrays, single longitudinal mode operation, circularly symmetric Gaussian output beams, and short cavity lengths.[4] However, the highest frequency obtained is 14 GHz for gain switching VCSELs, limited by high parasitics,[5] and 6 GHz for polarization modulation, limited by the thickness of the quarter-wave plate.[6] In this article, we present a polarization switching vertical-cavity surface-emitting laser having a tunable oscillation frequency as high as several terahertz. The substantial increase in frequency comes from using a new quarter-wave plate made of an amorphous silicon subwavelength transmission grating that is only one-third of the wavelength thick. The frequency tuning is provided by fabricating the wave plate and a mirror monolithically on a movable microcantilever.

II. PRINCIPLE OF POLARIZATION SWITCHING

The output of a conventional AlGaAs/GaAs VCSEL exists in two linearly polarized orthogonal modes along the ⟨011⟩ and ⟨011⟩ crystal directions, denoted as $P_{\parallel}$ and $P_{\perp}$.[7] In an isotropic cavity, these two modes have the same gains and are in competition, resulting in one mode being strong and the other mode weak. However, due to the equal gains, instability can occur when device operating parameters vary (e.g., injection current): the dominant lasing mode switches to the weak mode and vice versa. The polarization mode switching can also occur by injecting laser light that has the same mode as the VCSEL's weak mode into the VCSEL cavity.

In polarization switching, a partially reflecting mirror is placed outside a VCSEL output window, forming an external cavity, and a quarter-wave plate is placed between the VCSEL and the mirror, with the fast axis aligned 45° to the polarization direction. Illustrated in Fig. 1, as linearly polarized light (e.g., $P_{\parallel}$) from the VCSEL passes through the quarter-wave plate, it is converted to, say, right-hand circularly polarized (RHCP) light. The RHCP light is then converted to left-hand circularly polarized (LHCP) light as it reflects off the partial reflector. The LHCP light passes through the quarter-wave plate again and is converted back to linearly polarized light, except at an angle of 90° relative to the initial polarization (i.e., in the $P_{\perp}$ direction). The polarized light is injected back into the VCSEL and switches the polarization of the strong mode from the $P_{\parallel}$ to the $P_{\perp}$ polarization direction. Repetition of this cycle leads to an oscillation of the polarization state of the VCSEL at a frequency of

$$f = \frac{c}{4l}, \tag{1}$$

where c is the speed of light and l is the external cavity length (optical distance from the outer surface of the partial mirror to the mirror at the outer end of the VCSEL). This frequency corresponds to a period of twice the roundtrip time of light in the cavity.

Switching frequencies up to 6 GHz have been obtained by this method.[7] However, higher frequencies are difficult to

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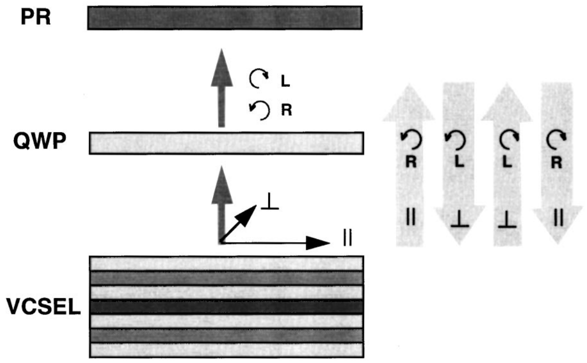

FIG. 1. Polarization switching VCSEL with a partial reflector (PR) and a quarter-wave plate (QWP). Polarized light (∥) is converted to right-hand circular polarization (R) by the QWP, reflected back in left-hand circular polarization (L) by the PR, and then switched to orthogonal polarization (⊥) by the QWP. Injection of polarized light back into the VCSEL switches the lasing polarization.

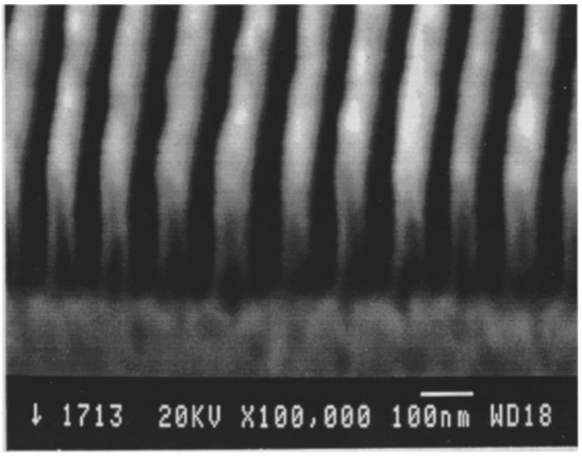

FIG. 2. 100 nm period α-Si SWG with 240 nm thickness and a filling factor of 0.45 on a silica substrate.

obtain since the minimum cavity length is limited by bulky optics, namely, the thick quarter-wave plate. To obtain higher frequencies, a thinner quarter-wave plate is required.

III. PRINCIPLE OF POLARIZATION SWITCHING USING A SUBWAVELENGTH GRATING QUARTER-WAVE PLATE

To increase the oscillation frequency of polarization switching VCSELs beyond the 10 GHz range, it has been suggested that a conventional quarter-wave plate should be replaced by a quarter-wave plate made of an α-Si subwavelength grating (SWG).[8] Because of its high birefringence, an α-Si SWG quarter-wave plate has a very small thickness, which allows the cavity length to be significantly reduced and the oscillation frequency to be in the terahertz range. The high birefringence can be explained using a simple form birefringence. In a dielectric grating, where the period is smaller than the wavelength of light, there will be two effective dielectric constants

$$\epsilon_{\parallel} = f\epsilon_1 + (1-f)\epsilon_2, \tag{2}$$

$$\epsilon_{\perp} = \frac{\epsilon_1\epsilon_2}{f\epsilon_2 + (1-f)\epsilon_2}, \tag{3}$$

where $\epsilon_{\parallel}$ is the effective dielectric constant along the grating, $\epsilon_{\perp}$ is the effective dielectric constant perpendicular to the grating, ϵ_1 is the dielectric constant of the grating material, ϵ_2 is the dielectric constant of the filling material, and f is the ratio of the grating width to the period.[9] When the dielectric constant of the grating (ϵ_1) is much larger than that of the filling material $(\epsilon_2), \epsilon_{\parallel}$ will be much larger than $\epsilon_{\perp}$, creating an artificial birefringent structure, with a phase retardation of

$$\Gamma = \frac{2\pi l}{\lambda}\left(\sqrt{\epsilon_{\parallel}} - \sqrt{\epsilon_{\perp}}\right), \tag{4}$$

where l is the thickness of the grating and λ is the wavelength of light. By using a material with a very high dielectric constant, such as α-Si, the birefringence of the grating will be two to three orders of magnitude larger than that of a natural crystal of the same thickness. This will allow a quarter-wave plate made of an α-Si SWG to be two to three orders of magnitude thinner than a conventional quarter-wave plate. By using a SWG wave plate with a phase retardation of 90° in place of the conventional quarter-wave plate, the cavity length can be significantly reduced, corresponding to a much higher switching frequency. Theoretically, if the cavity length can be reduced to 7.5 μm, a switching frequency of 10 THz can be expected.

It should be pointed out that subwavelength dielectric grating wave plates made of low refractive index materials such as photoresist,[10] quartz,[11] PMMA, and silicon nitride,[12] and also those made of α-Si (for 667 nm wavelength),[13] have previously been fabricated.

IV. FABRICATION OF A SWG WAVE PLATE

Amorphous silicon SWG wave plates especially designed for VCSELs with an output wavelength of 850 nm were fabricated. Amorphous Si was used because it has a high refractive index, which is necessary to bring up more than one eigenmode inside the grating to create polarization and phase changing effects, and to produce a large form birefringence. In the fabrication process, a 240-nm-thick α-Si layer was first evaporated on a 500 μm thick silica substrate. Polymethyl methacrylate (PMMA) with 950 000 molecular weight and 70 nm thickness was spun. Next, electron beam lithography was used to pattern the gratings with periods ranging from 50 to 900 nm and a filling factor of ~0.45. After development, a layer of Cr was evaporated and lifted off. This Cr pattern served as the mask in reactive ion etching (RIE) of the silicon, which used Cl_2, $SiCl_4$, and Ar_2 gases with flow rates of 40, 16, and 20 sccm, a pressure of 25 mTorr, and a power of 150 W. The Cr mask was stripped after the RIE. A scanning electron microscopy (SEM) micrograph of the cross section of a 100 nm period grating is shown in Fig. 2. The thickness is 240 nm and the filling factor is about 0.45. For 850 nm light, the grating has very

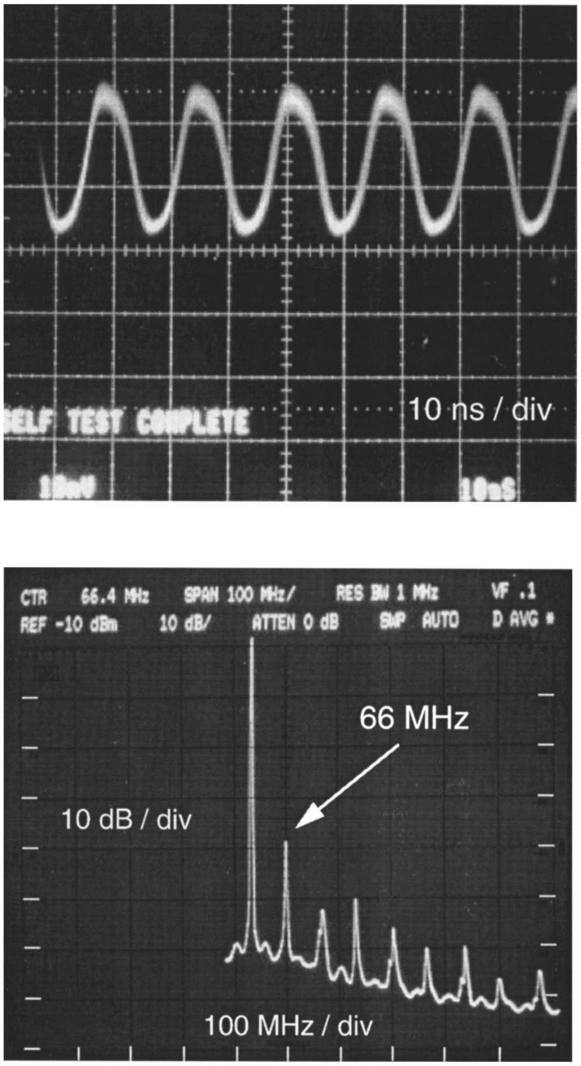

FIG. 3. Wave form and frequency spectrum of VCSEL output showing polarization switching. The external cavity length is 114 cm.

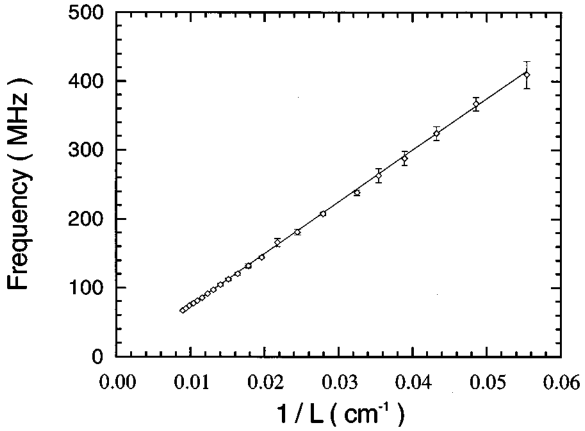

FIG. 4. Polarization switching frequency vs inverse cavity length when a conventional quarter-wave plate is placed between the VCSEL and the partial reflector. The period of switching is equal to two roundtrip times for light in the external cavity.

low absorption due to the small thickness and large band gap of the α-Si. The fabrication is similar to our previous work.[13]

V. EXPERIMENTAL RESULTS

Polarization switching was obtained using a conventional quarter-wave plate between a VCSEL and a partial reflector. The light, which passed through the partial reflector, was converted back to linearly polarized light outside the cavity using another quarter-wave plate. Switching of the polarization was detected using a linear polarizer and an avalanche photodiode. The switching was displayed on an oscilloscope and a spectrum analyzer (see Fig. 3). In this setup, modulation depths of up to 90% were obtained at 66 MHz, and switching frequencies between 50 and 500 MHz were measured (Fig. 4). The oscillation frequency was found to vary with the cavity length. Switching was obtained for all drive currents, but optimal results were obtained near the threshold current, which is 9 mA for the 20 μm VCSEL. Also, tilting of the quarter-wave plate in the cavity, simulating imperfect phase retardation, was shown to have little effect on the polarization switching. This indicates that a wave plate does not need to have a perfect 90° phase retardation. Rotation of the quarter-wave plate by a few degrees also had little effect on the overall polarization switching, although it did produce a split in the fundamental switching frequency.

Experimental and theoretical phase retardation of the SWG wave plate as a function of the period are shown in Fig. 5. The theoretical retardation was obtained using a rigorous modal expansion simulation. For small periods, the phase retardation can be calculated from form birefringence, and should be 90° for a rectangular grating with 0.50 filling factor. However, as the period decreases, the experimental phase retardation decreases. This is believed to be the result of imperfections in the grating profile and filling factor, which occurred when gratings with very small periods were fabricated. In order to act as a quarter-wave plate, a phase retardation of near 90° is required. The best period to use for a SWG quarter-wave plate is 150 nm, since it has a phase retardation of about 70°. Using a thicker grating can increase the phase retardation to 90° for this period. How-

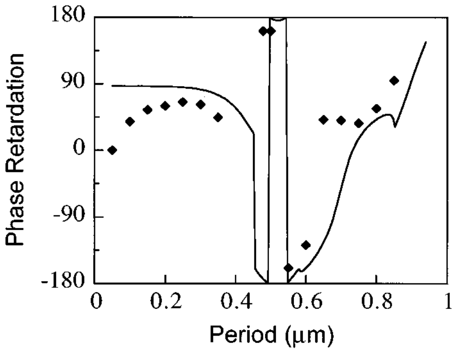

FIG. 5. Experimental and theoretical phase retardation for subwavelength gratings for different grating periods. The thickness of the gratings is 240 nm and the wavelength of the light is 850 nm. The points represent the experimental values and the line represents the theoretical values obtained using a rigorous modal expansion simulation.

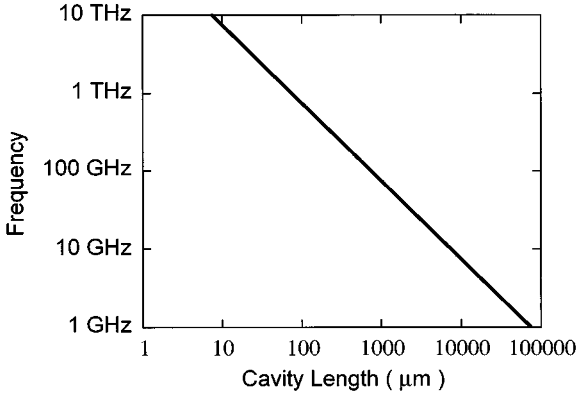

FIG. 6. Theoretical polarization switching frequency vs cavity length. A reduction of the cavity length to less than 75 μm would allow switching frequencies in the terahertz range.

ever, as discussed above, perfect phase retardation is not required since the VCSEL switches polarization with very little feedback.

By using the SWG wave plate with 240 nm thickness, integrated with a partial reflector, the external cavity length can potentially be reduced to several microns, corresponding to switching frequencies in the terahertz range (Fig. 6). Also, by mounting the partial reflector on a microactuator, such as a piezo or cantilever, the cavity length can be changed, allowing a tunable terahertz oscillator.

VI. SUMMARY

In summary, we have fabricated α-Si subwavelength gratings and have demonstrated their behavior as quarter-wave plates for certain grating periods. By placing the grating between a VCSEL and a partial reflector, a polarization oscillator can be produced. Because of the small thickness of the grating, the cavity length can be reduced to several microns, corresponding to switching frequencies in the terahertz range. Polarization oscillation using a conventional quarter-wave plate with frequencies between 50 and 500 MHz was demonstrated. By mounting the grating wave plate and partial reflector on a microactuator, the cavity length can be adjusted, producing a tunable terahertz oscillator.

[1] K. Y. Lau, Appl. Phys. Lett. **52**, 257 (1988).
[2] J. Wang and H. Schweizer, IEEE J. Selected Topics in Quantum Electron. **2**, 566 (1996).
[3] Y. K. Chen, M. C. Wu, T. Tanbun-Ek, R. A. Logan, and M. A. Chin, Appl. Phys. Lett. **58**, 1253 (1991).
[4] J. L. Jewell, J. P. Harbison, A. Scherer, Y. H. Lee, and L. T. Florez, IEEE J. Quantum Electron. **QE-27**, 1332 (1991).
[5] G. Shtengel, H. Temkin, P. Brusenbach, T. Uchida, M. Kim, C. Parsons, W. E. Quinn, and S. E. Swirhun, IEEE Photonics Technol. Lett. **5**, 1359 (1993).
[6] S. Jiang, Z. Pan, M. Dagenais, R. A. Morgan, and K. Kojima, Appl. Phys. Lett. **63**, 3545 (1993).
[7] M. Schimizu, F. Koyama, and K. Iga, Jpn. J. Appl. Phys., Part 1 **27**, 1774 (1988).
[8] S. Y. Chou (unpublished data, 1995).
[9] M. Born and E. Wolf, *Principles of Optics*, 6th ed. (Pergamon, New York, 1980), p. 705.
[10] L. H. Cescato, E. Glutch, and N. Striebl, Appl. Opt. **29**, 3266 (1990).
[11] R. C. Enger and S. K. Case, Appl. Opt. **22**, 3220 (1983).
[12] D. C. Flanders, Appl. Phys. Lett. **42**, 492 (1983).
[13] W. Deng and S. Y. Chou, J. Vac. Sci. Technol. B **13**, 2879 (1995).