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VCSEL Polarization Control for Chip-Scale Atomic Clocks

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Abstract

Sandia National Laboratories and Mytek, LLC have collaborated to develop a monolithically-integrated vertical-cavity surface-emitting laser (VCSEL) assembly with controllable polarization states suitable for use in chip-scale atomic clocks. During the course of this work, a robust technique to provide polarization control was modeled and demonstrated. The technique uses deeply-etched surface gratings oriented at several different rotational angles to provide VCSEL polarization stability. A rigorous coupled-wave analysis (RCWA) model was used to optimize the design for high polarization selectivity and fabrication tolerance. The new approach to VCSEL polarization control may be useful in a number of defense and commercial applications, including chip-scale atomic clocks and other low-power atomic sensors.

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CONTENTS

FIGURES

NOMENCLATURE

AC	alternating current
DARPA	Defense Advanced Research Projects Agency
DBR	distributed Bragg reflector
DOE	Department of Energy
LIV	light-current-voltage
MOCVD	metalorganic chemical vapor deposition
OPSR	orthogonal polarization suppression ratio
RCWA	rigorous coupled-wave analysis
SNL	Sandia National Laboratories
TE	transverse electric
TM	transverse magnetic
VCSEL	vertical-cavity surface-emitting laser

1. INTRODUCTION

Over the past few years, both Sandia and DARPA have invested heavily in a host of miniaturized sensor concepts based on integrated optical microsystems. Many of these microsystems employ a VCSEL as the optical source because of its inherent compactness, beam coherence, modulation bandwidth, and low power dissipation.

While VCSELs have many advantages, their combination of cylindrical symmetry and isotropic gain leads to polarization uncertainty and instability. Commercial VCSELs tend to be polarized along the [011] or [0-11] crystal axes; in these devices, the otherwise-degenerate polarization modes are split by a small amount due to anisotropies introduced during growth or fabrication. One polarization mode typically experiences higher gain and preferentially lases, but polarization switching can occur due to heating. The polarization change (and accompanying wavelength shift) can be extremely detrimental to microsensor operation, which generally demands a highly-stable laser source. Figure 1 shows the polarization-resolved output from a conventional VCSEL as a function of current, clearly illustrating the existence of orthogonal modes.

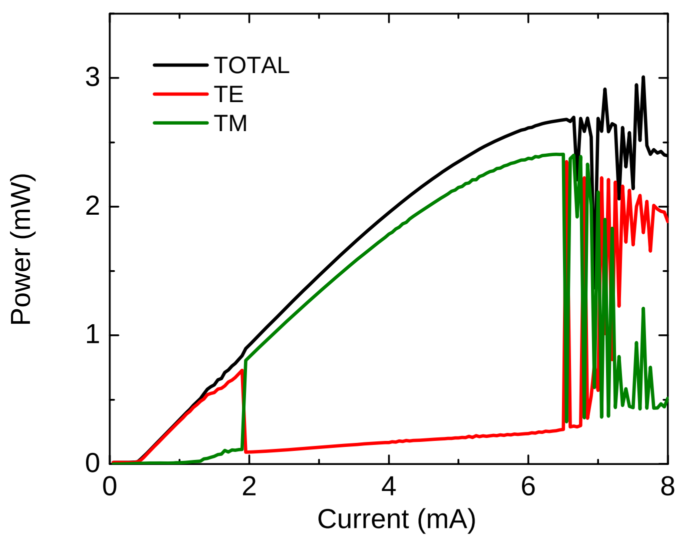

Figure 1. Polarization-resolved output from a conventional VCSEL as a function of current. Both TE and TM modes are present, and polarization mode competition occurs.

2. SURFACE GRATINGS FOR POLARIZATION CONTROL

Several approaches have been investigated for controlling VCSEL polarization. Most rely upon introducing a small amount of birefringence or gain anisotropy. The use of etched sub-wavelength diffraction gratings was suggested several years ago as a method of selecting polarization states in a more controlled manner [1,2] and has recently been demonstrated as a reliable approach to polarization stabilization [3,4]. In order to better understand the design principles and optimize the performance of such a device, we applied the rigorous coupled-wave analysis (RCWA) technique [5] to model the polarization selectivity of a VCSEL with an integrated surface grating. The device is illustrated in Figure 2.

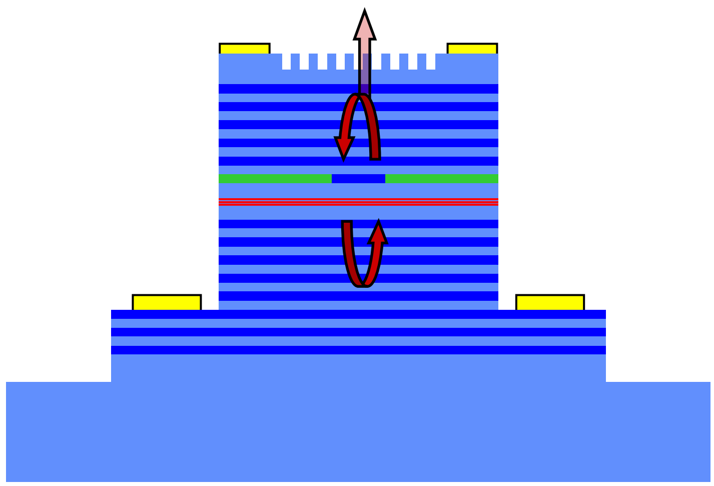

Figure 2. VCSEL with integrated surface grating for polarization control.

As an example of the optimization process, Figure 3 shows the calculated reflectivity of the upper DBR and surface grating for both TE and TM polarizations. In contrast to earlier work, we explore the deep-etch regime (i.e., greater than $\lambda/4$) in order to maximize polarization selectivity. Near a grating fill factor of 50%, the TM polarization sees a loss several times higher than that seen by the TE mode. Note that our design does not use a true sub-wavelength grating: the pitch is smaller than the emission wavelength, λ_o, but greater than λ (the wavelength in the semiconductor medium). This choice leads to a reduction in efficiency due to losses from higher internally-diffracted orders but maintains a single output beam. More importantly, it will allow the use of optical lithography instead of the electron-beam lithography typically required to fabricate sub-wavelength gratings.

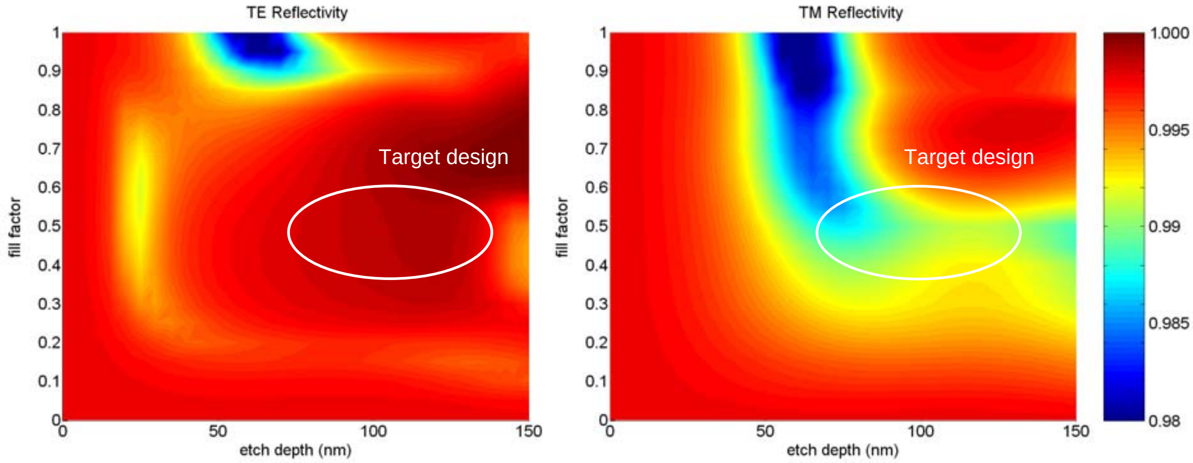

Figure 3. Reflectivity of the upper DBR and grating combination versus grating fill factor and etch depth for TE and TM polarizations. The broad fabrication window lies within a fill factor range of 40%–60% and an etch depth of λ/4 to λ/2.

3. DEVICE FABRICATION AND TESTING

The fabricated VCSELs were based on an 850-nm oxide-confined VCSEL design with the surface grating etched into the emitting aperture of the upper mirror, as shown in Figure 4. Gratings were oriented relative to the [011] axis at angles of 0°, 30°, 45°, and 90°, and several nearby devices were left unmodified for comparison. The semiconductor epitaxial structure, grown by MOCVD on an n-type GaAs substrate, consisted of a 36-period n-type AlGaAs DBR, a 5-quantum-well GaAs gain region, and 21-period p-type AlGaAs DBR. A 3λ/4 top layer on the p-DBR allowed etching of the gratings without exposing the high-aluminum-content layers below. An oxide aperture was used above the gain region to channel current and provide optical confinement. Figure 5 shows a photograph of an operational device during testing.

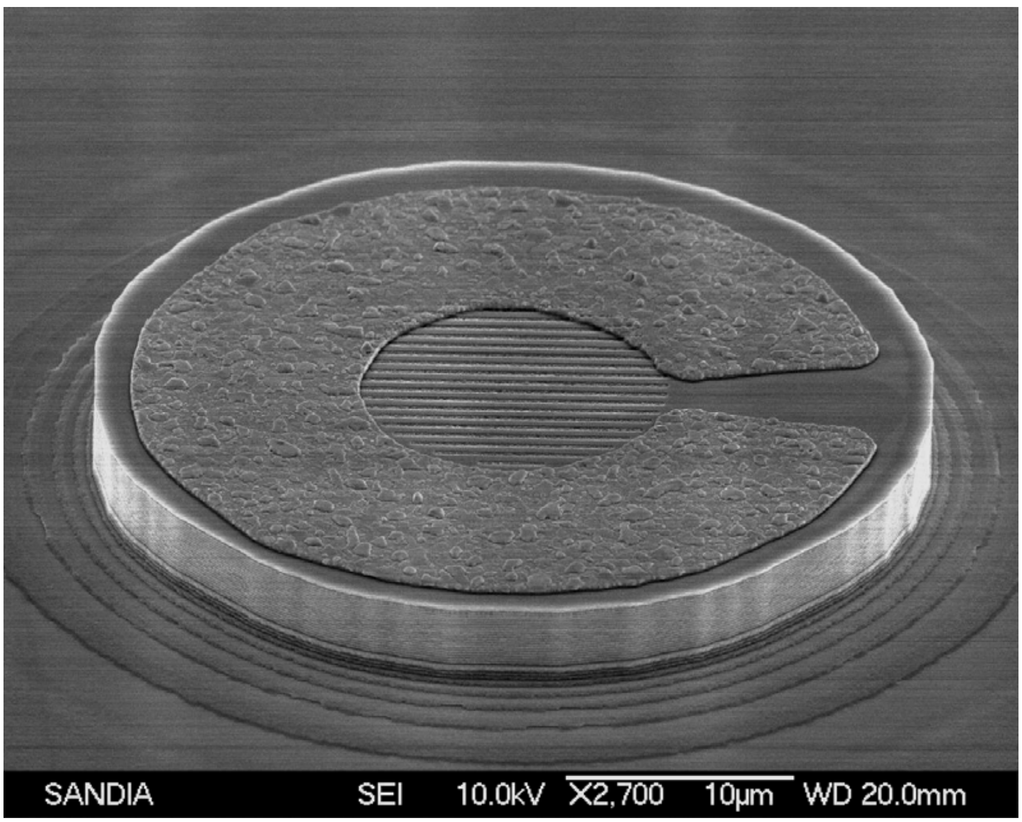

Figure 4. Scanning electron micrograph of a polarization-controlled VCSEL with etched surface grating.

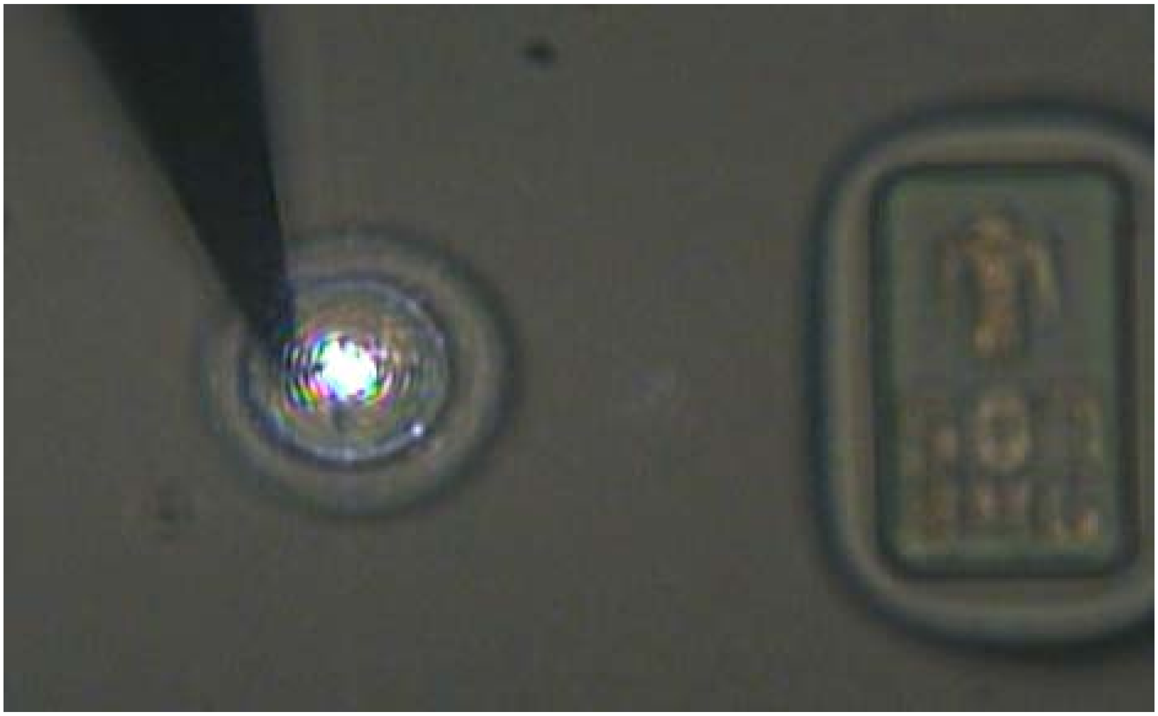

Figure 5. Polarization-controlled vertical-cavity surface-emitting laser in test setup.

Polarization-resolved LIV measurements were performed on several series of devices. The characteristics of a set of small-aperture single-transverse-mode lasers is shown in Figure 6. While both polarization modes lase in the unmodified devices, all of the grating VCSELs exhibit strong polarization pinning. Typical orthogonal polarization suppression ratios (OPSRs) were ≥15 dB, independent of grating angle. Larger-aperture multimode VCSELs showed similar or greater OPSR across their entire operating range.

Devices were also tested across a range of operating temperatures, and all grating VCSELs had stable single polarizations throughout the test. Most unmodified devices exhibited polarization switching over at least some temperature range. The instability of unmodified VCSELs was largely dependent on position on the wafer. Figure 7 shows representative data from a pair of neighboring devices.

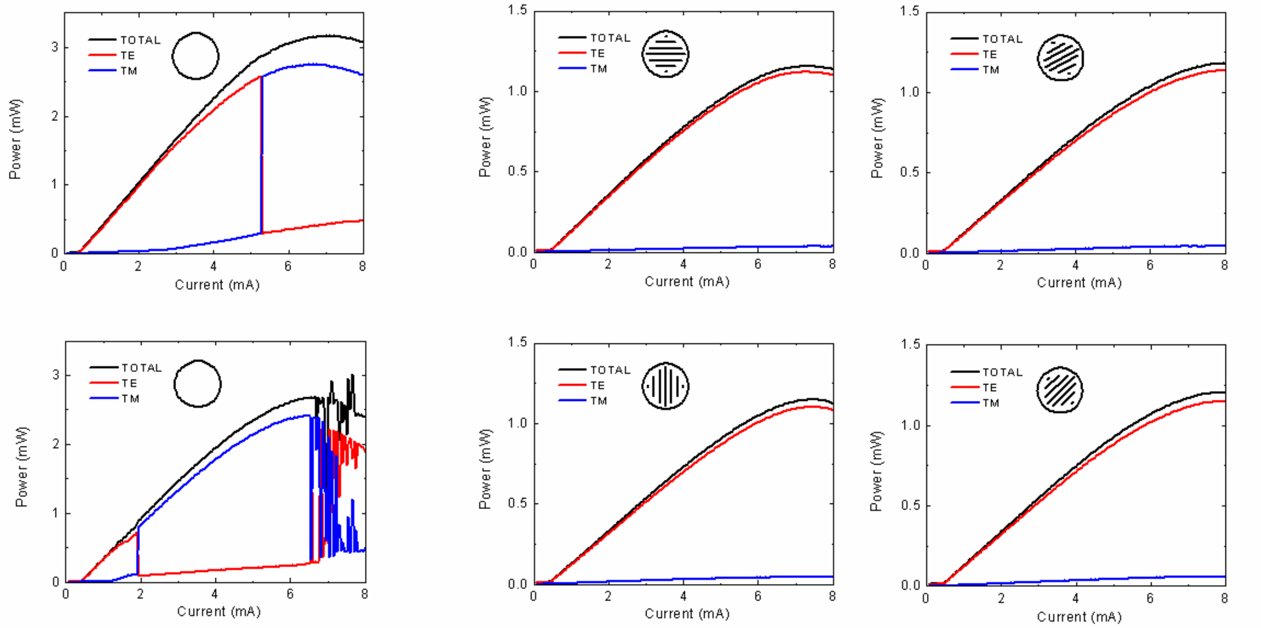

Figure 6. VI and polarization-resolved LI measurements for six neighboring VCSELs with oxide apertures of 2.5 µm. The devices shown in (a) and (f) have no surface gratings and exhibit switching between polarization modes. The gratings on devices (b) and (e) are perpendicular to one another and oriented along the major crystal axes. The gratings on lasers (c) and (d) are rotated at 30° and 45° respectively, as shown in the inset.

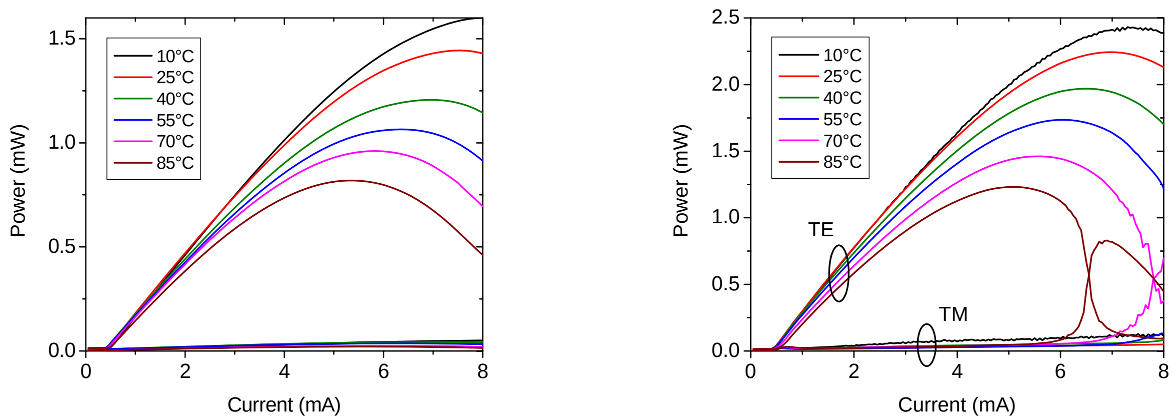

Figure 7. Polarization-resolved LI curves for a VCSEL with etched surface grating (left) and without a grating (right) over a large temperature range. The unmodified VCSEL exhibits polarization switching.

4. CONCLUSIONS AND SUMMARY

Sandia National Laboratories and Mytek collaborated under this CRADA to develop a new VCSEL assembly in support of the DARPA-funded Chip-Scale Atomic Clock program. The VCSEL assembly was designed to provide optical outputs with orthogonal polarization states using a monolithically-integrated pair of polarization-controlled VCSELs.

Sandia's role in this effort was to investigate different approaches to polarization control and demonstrate the most promising technique using a VCSEL operating at 850 nm. The most promising technique was found to involve etching nanoscale diffraction gratings into the output facet of the VCSEL. Models showed that these gratings provide strong polarization selectivity, and experimental results verified that the approach does yield the required performance. Sandia delivered five VCSEL assemblies that utilize this technique to generate pairs of optical outputs with orthogonal polarizations.

Mytek's role in this effort was to develop and deliver VCSELs operating at 795 nm to the DARPA chip-scale atomic clock effort. This work included epitaxial development, extensive fabrication, device characterization, and device packaging and delivery. Sandia worked with Mytek during parts of the VCSEL fabrication process, providing cleanroom capabilities that could not be secured elsewhere.

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