Physics of Widely Tunable VCSELs with Coupled Cavities

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Abstract: The behavior of a tunable VCSEL is governed by the resonances of a semiconductor cavity and an air cavity. By designing a semiconductor cavity which is antiresonant at the tuning center, the free spectral range is maximized at the edges of the tuning range.

Introduction

Vertical-cavity surface-emitting lasers (VCSELs) are the most commonly deployed light sources in optical communications due to their high direct modulation rate and low cost. VCSELs are also being deployed in new three-dimensional imaging applications such as optical coherence tomography (OCT), light detection and ranging (LIDAR), and structured illumination. Tunable VCSELs are deployed in swept-source OCT applications, where their wide tuning range and high sweep rate allow for high-resolution and high-throughput scans, respectively.

Tunable VCSELs generally comprise a fixed lower reflector, an active cavity, an air gap, and a movable upper reflector. The upper reflector – typically a high-contrast grating (HCG) or distributed Bragg reflector (DBR) – is supported by a microelectromechanical system with a thermal, electrostatic, or piezoelectric actuator to displace the reflector vertically [1] [2] [3]. The lasing wavelength is tuned by changing the length of the VCSEL cavity. In electrically pumped devices, the tuning range is limited by the free spectral range (FSR) of the VCSEL.

Due to the large refractive index contrast between semiconductor and air, the interface between the two can have a high enough reflectivity to divide the VCSEL into a system of two coupled cavities: one centered in the semiconductor and one in the air. Previous work to increase the FSR-limited tuning range of a VCSEL has focused on applying an antireflection (AR) coating at the interface in order to allow the VCSEL to resonate as one extended cavity (EC) [2] [4]. Recently, it has been shown that the tuning range can be extended even further without a significant increase in threshold material gain (g_{th}) by using an air cavity dominant (ACD) design [5].

Coupled Cavity Tunable VCSELs

A simplified structure is used in order to investigate the coupled cavity behavior of tunable VCSELs without AR coatings. This model consists of a semiconductor cavity with refractive index n_S and a variable length air cavity, all bounded by two idealized reflectors with $r = 0.999 + 0i$ for all wavelengths, as shown in Fig. 1. In all cases presented, the VCSEL is designed for emission at a center wavelength of $\lambda_C = 1060$ nm. Two cases are considered. In the semiconductor cavity dominant (SCD) case, the length of the semiconductor layer is set to $4\lambda_C$ so that the semiconductor cavity is resonant at λ_C and the VCSEL FSR is comparable to a realistic electrically pumped device. In the second case, which represents the ACD case, the length of the semiconductor layer is set to $4.25\lambda_C$ so that the semiconductor cavity is *anti*resonant at λ_C (the round-trip phase φ_{RT} is an odd multiple of π).

The resonances of each structure are calculated using the transfer matrix method by finding the wavelengths where φ_{RT} is a multiple of 2π. In addition to calculating the resonances of the entire VCSEL structure, the resonances of the constitutive semiconductor and air cavities are calculated by separating the simulation domain at the interface between air and semiconductor. These modes are plotted in Fig. 1 as a function of air cavity length. The semiconductor cavity modes, which are independent of the length of the air cavity, are shown in blue. The air cavity modes, which vary linearly with the air cavity length, are shown in red. Finally, the VCSEL modes are shown in black. The VCSEL modes follow the air and semiconductor cavity modes, avoiding crossings between the two.

The existence of two coupled cavities in a tunable VCSEL has an important consequence: the FSR of the VCSEL varies with wavelength and is limited by the cavity with the smallest FSR. Counterintuitively, this means that the VCSEL FSR is widest when the VCSEL mode is more confined within the cavity with the smallest FSR (the semiconductor cavity). Since an EC design has a much longer cavity than the semiconductor cavity alone, it has a lower FSR than one or both of the coupled cavity VCSELs at all wavelengths. Fig. 1(d) shows the VCSEL modes of all three designs for comparison. In order to capitalize on this increase in FSR, it is ideal to design a semiconductor cavity with modes that are far from λ_C by designing a semiconductor antiresonance at λ_C, as in an ACD VCSEL.

In order to illustrate the impact of increasing the FSR away from λ_C, a realistic VCSEL structure, including a lower DBR, a 1λ active cavity with multiple quantum wells, an oxidation layer, a contact layer, an airgap, and a movable HCG reflector, is considered in Fig. 2. In order to produce comparable SCD and ACD structures, the thickness of the contact layer is set to $\lambda_C/4$ and $\lambda_C/2$, respectively. In this analysis, the wavelength range is limited by the finite bandwidth of the semiconductor DBR. The air, semiconductor, and VCSEL cavities modes are shown in

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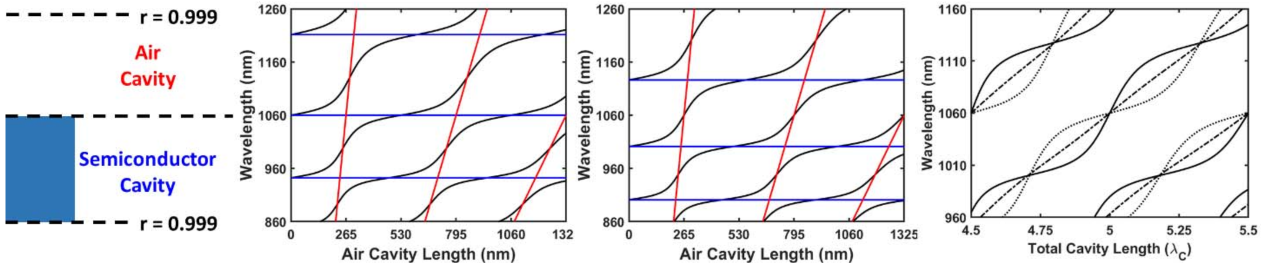
red, blue, and black, respectively. In order to calculate g_{th} as a function of air cavity length, gain is added to the quantum wells until the round-trip loss reaches zero. The dominant VCSEL modes with the lowest g_{th} are plotted with solid lines. The SCD device (Fig. 2b) has a semiconductor cavity antiresonance at λ_C. The ACD device (Fig. 2c) has semiconductor cavity modes at the edge of the DBR band, which results in a wider VCSEL FSR where adjacent VCSEL modes can compete. As a result, the ACD VCSEL has a significantly wider tuning range.

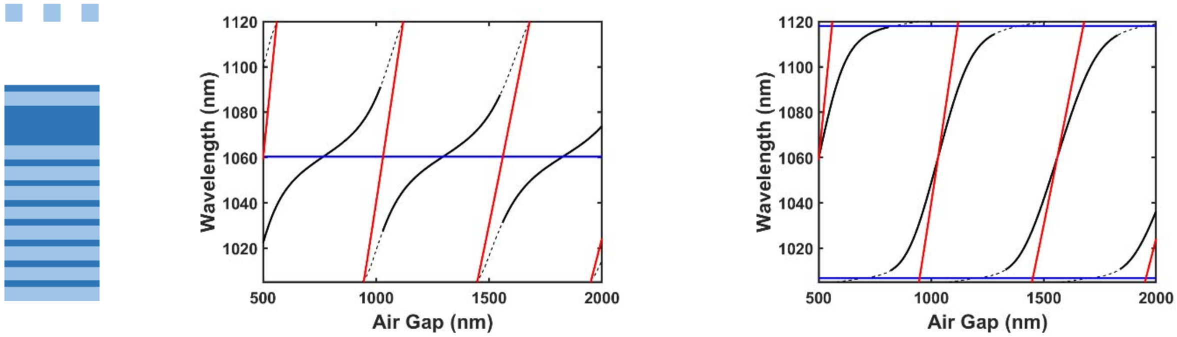
Conclusion

A tunable VCSEL is a system of an air and a semiconductor cavity, coupled by the layers placed at the interface between the two. As the VCSEL mode oscillates between the semiconductor and air cavities, the FSR changes dramatically. By designing the semiconductor resonance wavelengths appropriately, the FSR can be maximized at the edges of the tuning range, where mode competition can take place.



(a) (b) (c) (d)

Figure 1. Simplified VCSEL structure used to investigate the underlying physics of SCD and ACD tuning curves. (a) Schematic of simulated structure. (b) SCD and (c) ACD resonance curves for air (red), semiconductor (blue), and VCSEL (black) cavities. The ACD semiconductor cavity modes are shifted to higher wavelengths due to the longer semiconductor cavity. (d) Comparison between SCD, EC, and ACD tuning curves.



(a) (b) (c)

Figure 2. The tuning curve of a real coupled cavity VCSEL is bounded by the reflectance of the top and bottom reflectors. (a) Sketch of a realistic coupled cavity VCSEL with semiconductor DBR and HCG reflectors. (b) In an SCD VCSEL, the reflectance band contains a semiconductor cavity resonance at the center. The neighboring semiconductor cavity modes are outside of the band and the FSR enhancement is wasted. (c) In an ACD VCSEL, there is a semiconductor cavity antiresonance at the center of the reflectance band. The FSR enhancement increases the tuning range of the VCSEL.

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