Metal-Clad Subwavelength Semiconductor Lasers with Temperature-Insensitive Spontaneous Hyper-Emission

Joseph Smalley[1], Qing Gu[1], Matthew Puckett[1], Yeshaiahu Fainman[1]
Dept. of Electrical & Computer Engineering, University of California, San Diego, 9500 Gilman Dr., La Jolla, CA, USA 92093-5003
jsmalley@ucsd.edu

Abstract: Accounting for the temperature dependence of the cavity resonances and gain medium, we investigate a metal-clad subwavelength semiconductor laser with a spontaneous emission factor, β, approaching unity for all temperatures.
OCIS codes: (350.4238) Nanophotonics, (310.6188) Subwavelength structures; (250.5960) Semiconductor Lasers

1. Introduction

From mere curiosities operable at low temperatures only, Metal-Clad Subwavelength Semiconductor Lasers (MCSELs) have emerged as candidates for next-generation nanophotonic sources capable of room-temperature (RT), continuous wave (CW), electrically-pumped (EP) operation in ultra-dense arrays [1-3]. A particularly salient feature of MCSELs, compared to their more developed VCSEL counterparts, is their support of a spontaneous emission factor, β, which may approach unity for some temperatures [4]. While debate exists concerning its relation to the laser threshold [5], β may be viewed as a measure of the spontaneous emission efficiency of a particular cavity. It is defined as the ratio of spontaneous emission channeled into the dominant mode relative to emission into all modes, including other cavity modes, lossy modes and the freespace continuum. Herein, we concentrate on mode competition in cavities with subwavelength apertures. Therefore we define β_{MAX} as β_{MAX}=β in the absence of freespace coupling and refer to emission as hyper-emission when $\beta_{MAX}>0.5$.

According to a recent report, β_{MAX} may have a strong dependence on the temperature, as a result of detuning between the cavity resonance of the dominant mode and the material emission spectrum [6]. This may have significant consequences for the design and characterization of high-β light emitters. Because the cavity resonance depends upon the cavity geometry, however, the question arises on whether modifications may be undertaken that strike a balance between supporting high-β for all temperatures and prohibitively increasing the threshold gain. As we are concerned with operation near and below threshold, we assume throughout equivalence between the lattice and plasma temperatures, which are generally denoted by *T*.

2. Cavity Modes and Temperature

We consider two cavities, both similar to that used in the original demonstration of a fully-subwavelength RT semiconductor laser [7]. The first cavity, which we call Cavity 1, has core and total radii of R_{core}=225nm and R_{total}=325nm, respectively, with the difference made by the dielectric shield thickness. The second cavity, Cavity 2, is smaller with R_{core}=215nm and R_{total}=300nm. In each case, the shield thicknesses were optimized according to [8-9]. The cavities have identical dimensions in the longitudinal direction with active region and air plug lengths of 300nm and 480nm, respectively.

As can be seen in Fig. 1(a), Cavity 2 supports shorter resonant wavelengths for the corresponding modes supported by Cavity1, where we have determined the temperature dependence of the modes according to the method outlined in [6]. With the size reduction, the dominant TE_{011} mode blue-shifts ~75nm, while the HE_{121} mode blue-shifts only ~50nm. Consequently, the separation between the TE_{011} mode and its nearest spectral neighbor decreases from >80nm in Cavity 1 to ~60nm in Cavity 2. Additionally, the modal threshold gain of the TE_{011} mode of Cavity 2 exceeds that of Cavity 1, as seen in Fig. 1(b), and increases at a faster rate with temperature. Therefore, naively, it seems Cavity 1 will support a dominant TE_{011} mode with a larger β_{MAX} and lower threshold gain for all *T*. However, when the temperature dependence of the optical gain and spontaneous emission are taken into account we show evidence for the contrary.

3. Gain, Temperature, & the Spontaneous Emission Factor

Inclusion of the temperature dependence of the optical gain and spontaneous emission causes the TE_{011} mode of Cavity 1 to reside on the red side of the emission spectra at low temperatures, whereas that of Cavity 2 remains on the broad blue side of the emission spectra for all temperatures. Figure 2(a) shows the material gain at *T*=100K as a function of both wavelength and carrier density (pump) with the cavity resonances labeled according to the adopted scheme of Fig. 1. We observe that at low carrier densities the HE_{121} mode sees a much greater gain in Cavity 1. On the other hand, the TE_{011} mode always sees a higher gain than the HE_{121} mode in Cavity 2. Calculating β_{MAX} as a function of temperature for both cavities, following the method of [6], we see in Fig. 2(b) that Cavity 2 has a greater temperature integral of β_{MAX} than Cavity 1, counter to the naïve view. Further Cavity 2 supports spontaneous hyper-emission for all T up to room-temperature and maintains a relatively constant β_{MAX} compared to Cavity 1.

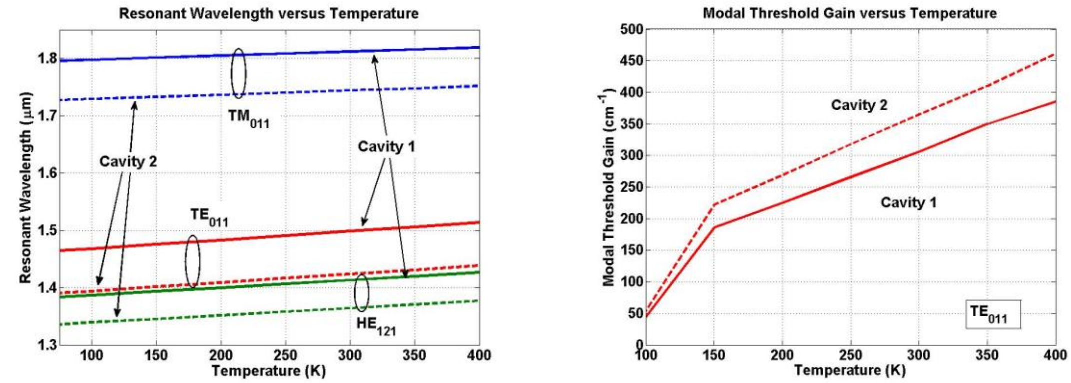

Fig. 1. (a) Resonant wavelength and (b) modal threshold gain for the TE_{011} mode and its nearest spectral neighbors for two different cavities. Cavity 1: R_{core}=225nm, R_{total}=325nm. Cavity 2: R_{core}=215nm, R_{total}=300nm.

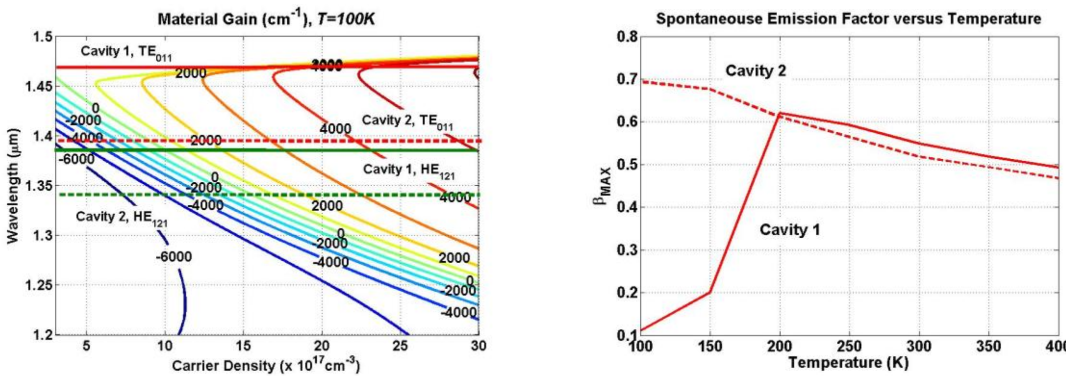

Fig. 2. (a) Material gain per unit length at T=100K as a function of wavelength and carrier density. The resonant wavelengths of the TE_{011} and HE_{121} modes for Cavities 1 and 2 at 100K are plotted for reference. (b) β_{MAX} as a function of temperature for Cavities 1 and 2.

An interesting question concerns the tradeoff between the improved $\beta(T)$ of Cavity 2 and the degraded threshold gain, relative to Cavity 1. A more exact threshold gain calculation ought to account for the improvement in β. However, for applications where coherence of the output is unimportant, the larger threshold gain may become irrelevant. We are in the process of fabricating such cavities to experimentally validate these findings.

This work was partially supported by NSF, the NSF's ERC-CIAN, ONR MURI, DARPA, and Cymer Corp.

[1] K. Ding et al., "Record performance of electrical injection sub-wavelength metallic-cavity semiconductor lasers at room temperature," Opt. Exp. **21**, 4728-4733 (2013).

[2] K. Ding and C. Z. Ning, "Metallic subwavelength-cavity semiconductor nanolasers," Light: Sci. App. **1**, e20 (2012).

[3] Q. Gu et al., "Sub-wavelength semiconductor lasers for dense chip-scale integration," Adv. Opt. Photon. *accepted*

[4] M. Khajavikan et al., "Thresholdless nanoscale coaxial lasers," Nature 482, 204-207 (2012).

[5] C. Z. Ning, "What is the lasing threshold," J. Sel. Top. Quant. Elect. **19**, 4, 1503604 (2013)

[6] J. S. T. Smalley et al., "Temperature dependence of the spontaneous emission factor in subwavelength semiconductor lasers," IEEE J. Quant. Elect. *accepted*

[7] M. P. Nezhad et al., "Room-temperature subwavelength metallo-dielectric lasers," Nat. Photon. **4**, 395-399 (2009)

[8] A. Mizrahi et al., "Low threshold gain metal coated laser nanoresonators," Opt. Lett. **33**(11), 1261-1263 (2008)

[9] J. S. T. Smalley et al., "Invariance of optimal composite waveguide geometries with respect to permittivity of the metal cladding," Opt. Lett. **38**(23), 5161-5164 (2013).