Nanoscale Light Sources for On-chip Optical Interconnects

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Abstract

Near-infrared semiconductor lasers with nanoscale physical dimensions and effective mode volumes using metallodielectric cavities are discussed. Such ultra-small lasers will find various applications in on-chip optical communication, data storage, and sensing.

1 Introduction

For seamless integration of electronics and photonics technologies in a single unified chip-scale platform, one of the most impending issues is the development of novel photonic devices that match the size of electronic devices [1]. The length scale of electronic transistors is currently sub-100 nm thanks to the advance of micro/nano-fabrication technologies. However, the physical sizes of conventional optoelectronic light sources with visible and near-infrared emission wavelengths are usually in the micrometer range due to the diffraction limit. The development of efficient high-performance nanoscale light source therefore has a big potential for high-performance optoelectronic integrated circuits.

In addition to optical interconnect applications, coherent light sources with subwavelength length scales are of considerable interest in view of their wide range of applications, such as optical signal processing, data storage, biological/chemical sensing, and imaging. Subwavelength light emitters with extremely small mode volume can achieve fundamental advantages over the conventional lasers in terms of enhanced light-matter interaction, low threshold, and single frequency operation, leading to novel functionalities and superior performances for emerging applications in on-chip optical interconnects. As the optical cavity mode volume decreases, the spontaneous emission rate can be enhanced inversely proportional to the effective mode volume via the Purcell effect, and large spontaneous emission coupling to the highly confined resonant optical mode will ultimately result in ultra low power laser operation.

For on-chip optical interconnect applications where dense integration and small footprint requirements are stringent, the overall physical size of the lasers and their scaling issues have important implications in practical implementation of the whole communication systems [2, 3]. In this invited paper, we review the recent trend of nanoscale semiconductor light sources for optical interconnect applications.

2 Subwavelength-scale laser cavities

To reduce the overall laser volume, a number of laser cavity structures have been theoretically investigated and experimentally demonstrated. For example, photonic crystal lasers employ dielectric photonic bandgap resonators, and result very small effective mode volume close to the diffraction limit. One-dimensional photonic crystals, such as Bragg mirrors, were first used to form Fabry-Perot resonators in vertical cavity surface emitting laser configurations with relatively large mode volumes. More recently, lasing action from the fundamental monopole mode of two-dimensional photonic crystals with optical and electrical injection in room temperature was experimentally demonstrated [4]. In order to create wide photonic bandgap for tight optical confinement, however, the photonic crystal structures have to cover multiple wavelengths in the lateral dimension, and the overall laser size becomes much bigger than the effective mode volume: the region where the lightwave is confined [4].

In addition to the photonic crystal geometries, microor nanoscale disks have also been used to confine the lightwave inside the cylindrical dielectric resonators for laser operation using total internal reflection. Laser output from the whispering gallery mode is convenient to couple to the in-plane waveguides, and thus can be readily integrated for photonic interconnect applications. Due to such advantages, there are a number of attempts to integrate microdisk lasers onto the planar lightwave circuits and silicon substrates. However, the radiation loss increases exponentially with smaller azimuthal mode numbers, and it is exceedingly difficult to maintain high quality factor at low-order modes.

To overcome the limit of dielectric optical cavities, metallodielectric resonators have been recently investigated to further reduce the effective mode volume and the physical size of the laser [2, 3, 5]. Using metal-coated cavities, the effective mode volume below the diffraction limit [2, 5] and the physical laser volume smaller than the emission wavelength in all three dimensions [2, 3] have been achieved. Semiconductor lasers with all three dimensions smaller than wavelength are interesting because their sizes start to approach those of transistors in silicon integrated circuits. Such nanoscale lasers can be integrated alongside transistors for on-chip optical interconnect in high performance computer chips.

In next sections, we review our recent demonstration of subwavelength-scale semiconductor nanopatch lasers with cylindrical metallodielectric resonators [2]. We observe lasing in the two fundamental optical modes, which resemble oscillating electrical and magnetic dipoles. For the first lasing mode (electrical dipole mode), the physical volume of the nanopatch laser is only 0.019 cubic wavelength (0.056 μm^3 at 1420 nm wavelength), and the laser diameter and thickness are 406 and 440 nm, respectively.

3 Metallodielectric cavity design

The nanopatch semiconductor laser structure and the scanning electron micrograph of a typical fabricated device are shown in Fig. 1. A cylindrical semiconductor gain medium is sandwiched between a circular metal patch and a bottom ground plane. To reduce non-radiative recombination at the etched sidewalls with a high surface-to-volume ratio, InGaAsP is used as the semiconductor optical gain material. Gold is used for both metal layers, and the size and shape of the circular metallic patches, which defines the resonant wavelength, is defined by electron-beam lithography. The metal thickness (~80 nm) is chosen to be much larger than the field penetration depth at the near infrared region. The radius, r, is varied from 200 to 310 nm, and the total thickness of the semiconductor and dielectric layers between the metal planes is h=230 nm.

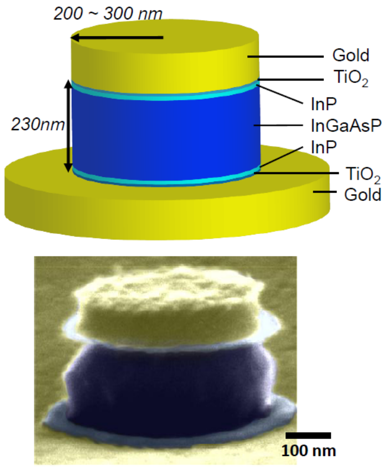

Fig. 1. Schematic diagram and scanning electron micrograph of a semiconductor nanopatch laser.

The cylindrical nanopatch resonators with two metal planes can be simply modeled using ideal boundary conditions with perfect electric conductors at the dielectric-metal interface and a perfect magnetic conductor at the semiconductor sidewall [2]. The fundamental eigenmode of the nanopatch cavity with perfect conductor boundary conditions is a TM_{111}-like mode that resembles oscillating electrical dipoles. Electric field lines are almost linearly polarized and mostly terminate on free charges in the metal layers, and most of the optical mode energy is confined to the middle of the gain region with a high confinement factor of 84%. Since the radiation is significantly suppressed, most of the optical energy is lost from resistive heating in the metal. Although the optical losses practically set an upper bound of the cavity quality factor, it is still larger than pure dielectric microdisk resonators with the same subwavelength dimensions.

The second-order mode is a TE_{011}-like magnetic dipole mode, which corresponds to a whispering gallery mode with an azimuthal mode number of 0 and a radial mode number of 1. This mode is commonly called as a monopole mode in photonic crystal slab resonators. The radiation is not completely suppressed as in the first-order mode, but the mode profile overlaps less with the metal layers than the fundamental mode. As a result, the overall quality factor and the effective mode volume are both larger than the fundamental mode. This magnetic dipole mode is nondegenerate, while the electric dipole mode is doubly degenerate in two orthogonal directions. In the far field regime, the electric dipole mode radiates surface normal, and the magnetic dipole mode radiates in-plane with the device, making it more suitable for integration with planar lightwave circuit technologies.

4 Laser characteristics

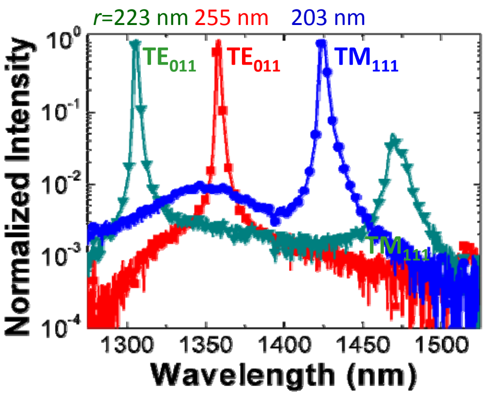

Fig. 2. Laser emission spectra for three different nanopatch sizes (r=203, 223, 255 nm). The lasing mode migrates from the electrical to magnetic dipole mode as the nanopatch size increases.

To reduce metal loss and non-radiative recombination and increase the semiconductor optical gain, we performed our laser characterization at low temperature (78 K). We expect to obtain room-temperature lasing when the cavity dimensions become bigger, and the higher-order mode resonances with higher quality factors overlap with the optical gain region, as discussed in [3].

Single-mode lasing with relatively large side-mode suppression (>20 dB) was observed for most cavity radii (Figs. 2 and 3). While small nanopatch cavities whose radius is less than 215 nm lase in the fundamental electric dipole mode (TM111), larger cavities lase in the magnetic dipole mode (TE011). The cavity quality factors for the electric and magnetic dipole modes are experimentally estimated to be 132 and 168, respectively. The effective mode volumes for the electric and magnetic dipole modes, estimated from computer simulations, are $0.54(\lambda_{TM}/2n_{eff})^3$ and $2.99(\lambda_{TE}/2n_{eff})^3$, respectively, where n_{eff} is the effective refractive index of the laser cavity.

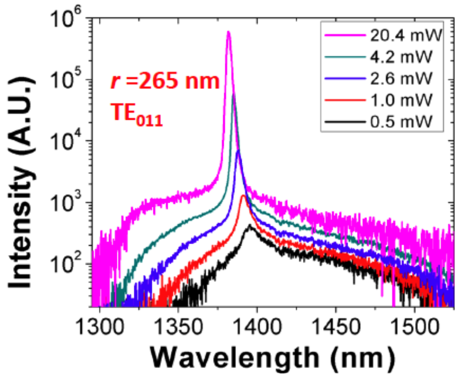

Fig. 3. Evolution of the emission spectra with increasing peak pump power for nanopatch lasers with 265 nm radius, which lases in magnetic dipole mode.

5 Conclusion

Subwavelength-scale semiconductor nanopatch lasers at near infrared wavelengths are frequency-scaled versions of conventional microwave resonators with very high optical confinement factors. Contrary to common belief, the presence of metal can improve the quality factor of subwavelength optical resonators by suppressing the radiation into the free-space. We believe that the use of conductive metal structures for both light confinement and electrical carrier injection in ultra-small coherent light sources will facilitate the integration of optical components with nanoscale electronic devices.

6 References

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