Metallo-dielectric nanolaser coupled to an InP-membrane waveguide

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A design for a metallo-dielectric nanolaser with electrical injection and coupled to an InP-membrane waveguide is presented. The structure supports a dielectric lasing mode near 1.55 μm with a high Q-factor due to a reflective metallic cladding. Threshold gain levels below 1000 cm^{-1} are predicted, which are compatible with room temperature operation under a current injection of a few tens of microamperes. Due to an efficient coupling to the waveguide, it represents a promising laser structure for ultra-compact photonic integrated circuits.

Introduction

In the last years, a new type of semiconductor lasers with metallic cavities has been demonstrated to overcome losses and achieve lasing with either dielectric or plasmonic modes [1,2]. These devices have generated a large interest in view of their potential for low current operation, ultra-fast modulation, large scale integration and high cross talk immunity, and several coupling mechanisms are being investigated for their on-chip integration [3,4]. The combination of dielectric and metallic confinement can lead to strong optical confinement with relatively low loss, and has been used to demonstrate room-temperature lasing in a subwavelength cavity [5]. However, efficient coupling to a waveguide has not been demonstrated yet. In Ref. [4] the coupling of a III-V metallo-dielectric nanopillar laser to a Si/SiO_2 waveguide was proposed. In this contribution, a metallo-dielectric cavity laser coupled to a waveguide on a III-V membrane bonded with BCB to silicon is described and studied by means of 3D finite-difference time-domain simulations. These membranes have been recently proposed as a platform for the integration of ultra-small active components [6].
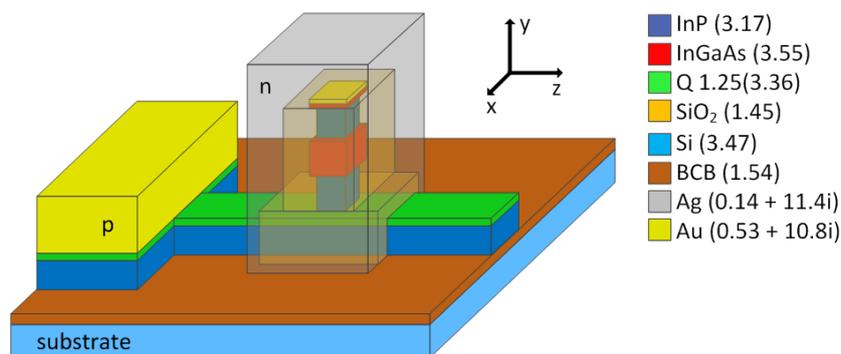

Figure 1. Model of the metallo-dielectric laser coupled to an InP-membrane waveguide.
The refractive index of each material at 1.55 *μm* is shown in parenthesis.

The proposed laser structure is shown in Fig. 1. The semiconductor laser pillar lies on top of a thin InP waveguide and it is insulated with a SiO_2 layer from a metallic cladding. A lateral p-contact is electrically connected to the pillar through a highly

doped quaternary (InGaAsP) layer. The metallic cladding acts itself as the n-contact allowing a top-down current flow. For simplicity, Fig. 1 does not show the ohmic contact layers Ti/Pt/Au, however they were included in the simulation model in order to consider their optical loss.

Figure 2a shows the geometry of the cavity. The influence of the thickness t of the SiO$_2$ insulation layer, the undercut s and the bottom post cladding h on the Q-factor and optical efficiency of the laser is reported below. The undercut, which is the same in both x and y directions, was introduced to improve the quality factor while maintaining a short bottom post. The simulated quality factor of the cavity is shown in Fig. 2b as a function of the undercut and bottom post height. A higher bottom post leads to an increased Q-factor due to a reduced coupling with the waveguide. Likewise, a larger undercut improves the Q-factor. An undercut of $60\,nm$ was considered for the simulation results presented in the following.
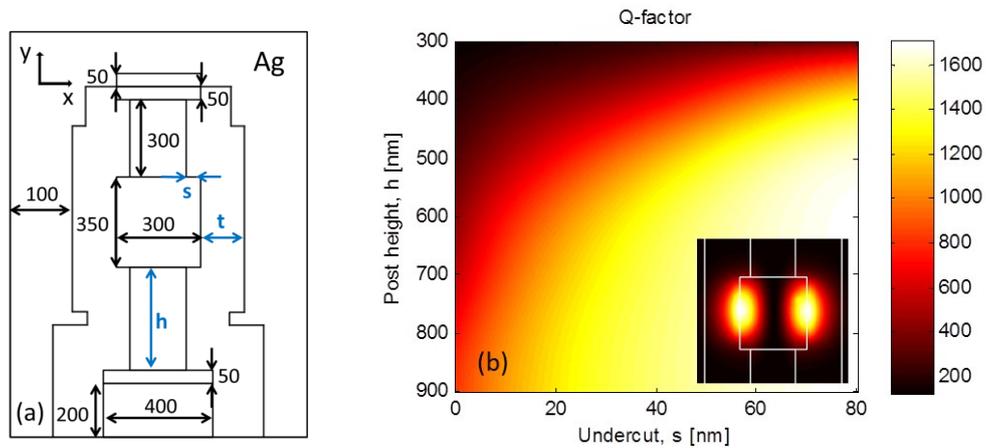

Figure 2. (a) Schematic of the cavity with dimensions in nanometers. The optimization parameters are shown in blue. (b) Q-factor as a function of undercut and post height for an insulation thickness $t = 175\,nm$. The inset shows the modulus squared of the electric field distribution of the TE polarized mode in the xy plane across the center of the cavity.

Quality factor and coupling properties

For the optimization of the insulation thickness t of the cavity, a bottom post height $h = 700\,nm$ was initially considered, since it provides sufficient isolation from the waveguide as suggested in Fig. 2b. Additionally, the pillar laser is considered to be symmetric along x and z (i.e. the length and width of the active medium are both $300\,nm$). For a thin insulation layer, metal losses are high, whereas the radiation losses increase for a thick insulation. Therefore, there is an optimum insulation thickness ($t = 175\,nm$) where the Q-factor is maximum as can be seen in Fig. 3a. The resonant wavelength for this thickness is around $1.4\,\mu m$, nevertheless it will be shown later that this can be increased to $1.55\,\mu m$ by changing the aspect ratio of the cavity.

Once the optimum insulating thickness has been found, the bottom post height is varied in order to increase the coupling to the waveguide. The total loss rate in this nanopillar laser can be written as the sum $\gamma_{total} = \gamma_{metal} + \gamma_{sub} + \gamma_{wg}$ of the loss into the metal, the radiation into the substrate and the useful coupling to the waveguide [4]. We define the optical efficiency of the cavity as $\eta_o = (\gamma_{sub} + \gamma_{wg})/\gamma_{total}$ (ratio of total radiated power to total lost power). Its dependence on the post height is shown in Fig. 3b. As

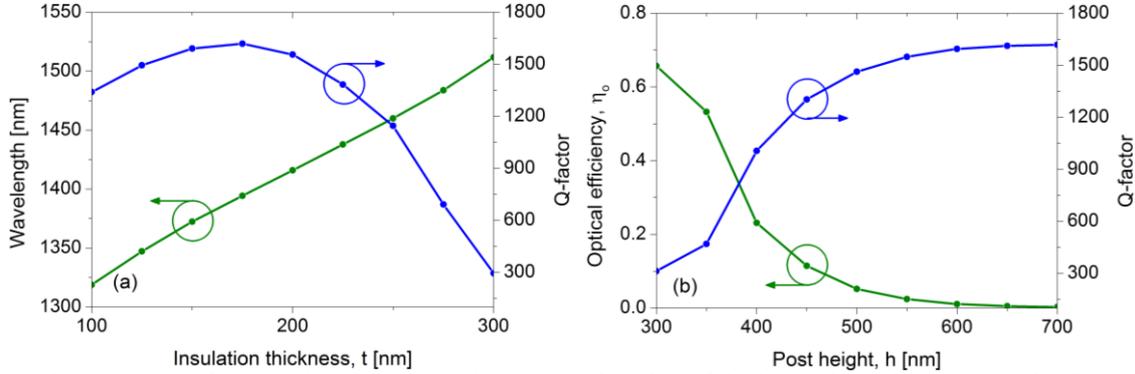expected, the optical efficiency increases at the expense of the Q-factor when decreasing the post height.

Figure 3. (a) Q-factor and resonant wavelength as a function of the insulation thickness, considering $h = 700\ nm$. (b) Q-factor and optical efficiency for a varying bottom post height, considering $t = 175\ nm$.

A symmetric cavity has been considered until now, however the coupling efficiency can be increased by breaking the symmetry of the cavity, which can be realised by elongating the cavity in the z-direction [4]. The coupling efficiency η_c is defined as the ratio between the power coupled to the waveguide (in both directions) and the total radiated power: $\eta_c = \gamma_{wg}/(\gamma_{sub} + \gamma_{wg})$. Figure 4 shows an increase in coupling efficiency and resonant wavelength for an elongated cavity, while the Q-factor decreases. The desired lasing wavelength of $1.55\ \mu m$ is achieved for a cavity length of $400\ nm$.
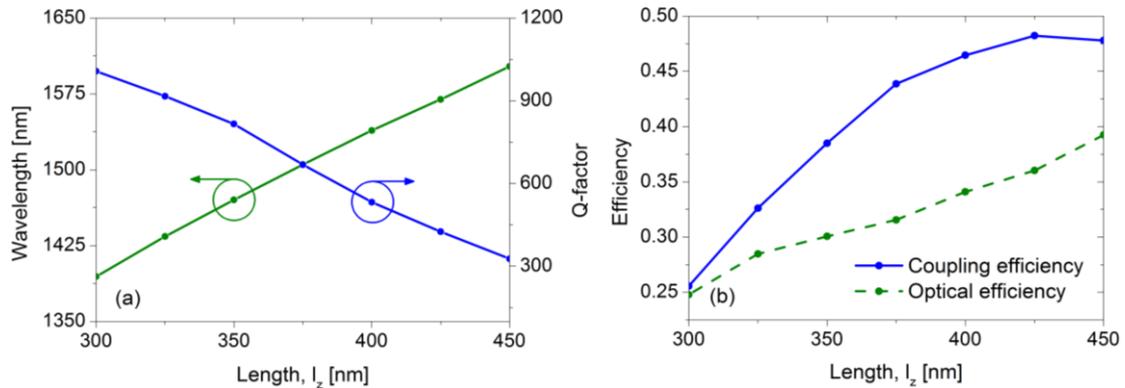

Figure 4. (a) Q-factor and resonant wavelength for an elongated cavity with active medium length l_z. (b) Improvement of optical and coupling efficiencies by elongating the cavity. Both graphs consider $t = 175\ nm$ and $h = 400\ nm$.

Differential efficiency and threshold conditions

The differential quantum efficiency determines the final amount of optical power coupled to the waveguide, and it is given by $\eta_d = \eta_o\eta_c$, assuming a unity internal quantum efficiency. Figure 5a shows the differential efficiency and the threshold gain of the asymmetric cavity. The threshold gain is calculated as $g_{th} = 2\pi n_g/Q\Gamma\lambda_0$, where n_g is the group velocity of the active medium, Q is the cavity quality factor, Γ is the confinement factor and λ_0 is the resonant wavelength in vacuum. According to our simulations, the confinement factor in the cavity varies almost linearly from 0.4 to 0.28 for a cavity length varying from $300\ nm$ to $450\ nm$. As a result, Fig. 5 shows that the

metallo-dielectric laser studied offers a much better performance than previously proposed waveguide-coupled plasmonic lasers [7].
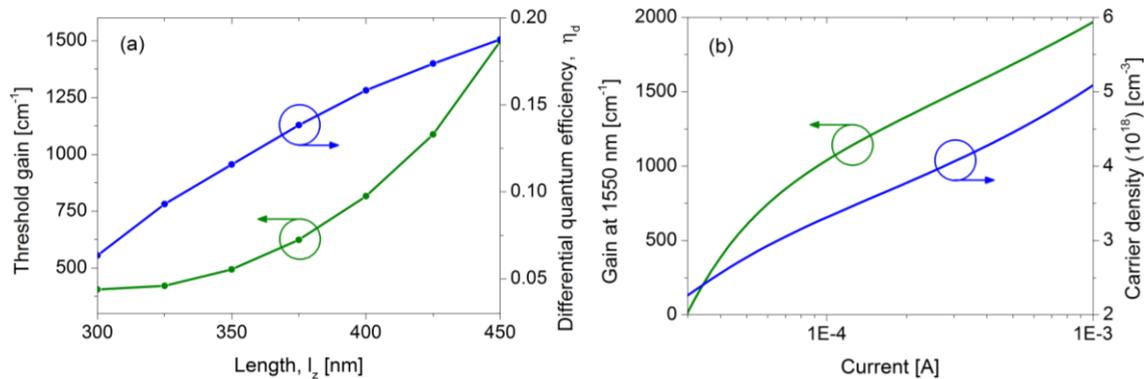

Figure 5. (a) Lasing threshold gain and differential quantum efficiency as a function of the cavity length. (b) Material gain of InGaAs and carrier density as a function of injection current.

Finally, Fig. 5b shows gain-current calculations performed in order to estimate the threshold current expected in the proposed laser device. The material gain curve was calculated from the transition matrix element and assuming parabolic bands [8], and the carrier density was calculated with a 2D self-consistent Poisson solver.

Conclusions

The design of a metallo-dielectric laser operating near $1.55 \, \mu m$ coupled to a thin InP waveguide has been presented. The influence of the main structural parameters was studied to optimize its performance. The optimized cavity has an insulation thickness of $175 \, nm$ to maximize the Q-factor, a bottom post height of $400 \, nm$ and a cavity length of $400 \, nm$ to provide a high differential efficiency. This results in a low threshold gain of $815 \, cm^{-1}$, which can be reached with a current injection of about $70 \, \mu A$ at room temperature.

Acknowledgments

References

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