# Low threshold gain metal coated laser nanoresonators

**Amit Mizrahi,* Vitaliy Lomakin, Boris A. Slutsky, Maziar P. Nezhad, Liang Feng, and Yeshaiahu Fainman**

*Department of Electrical and Computer Engineering, University of California, San Diego, 9500 Gilman Drive, La Jolla, California 92093-0407, USA*

**Corresponding author: amitmiz@ece.ucsd.edu*

Received March 17, 2008; accepted April 20, 2008;
posted April 30, 2008 (Doc. ID 93956); published May 30, 2008

We introduce a low refractive index layer between the metal and the gain medium in metal-coated laser resonators and demonstrate that it can significantly reduce the dissipation losses. Analysis of a gain medium waveguide shows that for a given waveguide radius, the low index layer has an optimal thickness for which the lasing threshold gain is minimal. The waveguide analysis is used for the design of a novel three-dimensional cylindrical resonator that is smaller than the vacuum wavelength in all three dimensions and exhibits a low enough threshold gain to lase at room temperature. © 2008 Optical Society of America

*OCIS codes:* 140.3410, 140.4780, 310.6628, 140.5960, 350.4238.

Subwavelength laser sources are expected to be key components in future nanophotonic circuits. Current microscale semiconductor laser resonators may attain small modal volumes but require structures that are large compared to the wavelength, such as photonic crystals [1] or Bragg mirrors [2]. Metallic coatings provide stronger confinement of light and consequently higher device-packing density and therefore have been proposed for reducing the size of semiconductor nanowire lasers [3,4]. The drawback of using metals, however, is their high dissipation losses at optical frequencies. Recently, lasing in three-dimensional (3D) subwavelength metal-coated cavities has been reported [5], but the structure had to be cooled down to cryogenic temperatures to reduce the dissipation losses in the metal and increase the gain in the semiconductor. To the best of our knowledge no similar device working at room temperature has been demonstrated yet.

In this Letter, we show that the losses in metal-coated gain waveguides, as well as 3D laser resonators, can be significantly reduced by introducing a low index "shield" layer between the gain medium and the metal. We begin by considering a composite gain waveguide (CGW) having a gain medium cylindrical core, a shield layer, and a metallic coating, as shown in Fig. 1(a). For a given CGW cross section size, the shield layer thickness is then tuned to maximize the confinement of the electric field in the gain medium and reduce the field penetration into the metal. By that, we increase the ability of the device to compensate for the dissipated power with power generated in the gain medium. A direct measure of that is the threshold gain, i.e., the gain required for lossless propagation [6] in the CGW. The field attenuation in the shield layer resembles that of Bragg fibers [7]. The layer adjacent to the core, in particular, is of high importance [8] and is also used to reduce loss in infrared hollow metallic waveguides [9].

Subsequently, we use the CGW model for the design of subwavelength 3D resonators. To confine the light in the longitudinal direction, the CGW is terminated from both sides by a low index "plug" region covered with metal, which forms the closed cylindrical structure shown in Fig. 1(b). A more practical nanolaser configuration from a fabrication point of view is the open structure with a $SiO_2$ substrate shown in Fig. 1(c). The inherent radiation losses into the substrate provide means for collecting the laser light, in contrast to the closed structure, where extracting light requires modification of the metal coating, such as making a hole in it. The threshold gain for the 3D resonators, defined as the gain required to compensate for the metal losses in the closed structure or to compensate for both the metal and the radiation losses in the open structure, is shown to be sufficiently low to allow laser action at room temperature.

Let us first consider the infinite CGW of Fig. 1(a), with relative permittivities $\varepsilon_g=\varepsilon_g'+j\varepsilon_g''$, $\varepsilon_s$ and $\varepsilon_m=\varepsilon_m'-j\varepsilon_m''$ of the gain medium, the shield layer, and the metal, respectively. Assuming a time dependence of $\exp(j\omega t)$, we have $\varepsilon_g'',\varepsilon_m''>0$. The radius of the gain medium is $R_g$, the shield layer thickness is $\Delta=R_{out}-R_g$, and the metallic coating layer begins at radius $R_{out}$. The eigenmodes of the CGW may be derived from the general solution of the longitudinal fields in each layer having the form

$$U=[AJ_m(k_r r)+BY_m(k_r r)]f(m\phi)e^{-j\beta z}, \qquad (1)$$

where $U=E_z$ or $H_z$; $J_m$ and $Y_m$ are Bessel functions of the first and second kind, respectively; $k_r=\sqrt{k_0^2\varepsilon-\beta^2}$, $k_0=\omega/c$; $\varepsilon$ is the relative permittivity of the layer; and $f(m\phi)$ may be expanded by $\exp(\pm jm\phi)$, where the integer $m$ is the azimuthal index. The dispersion relation is found using the transfer matrix method [7]. For the threshold gain $\varepsilon_g''$, the propagation constant $\beta$ is real, and the threshold gain explicitly satisfies

$$\varepsilon_g''=\varepsilon_m''\iint_{\text{Metal}}\mathrm{d}A|\vec{E}|^2 \Bigg/ \iint_{\text{Gain}}\mathrm{d}A|\vec{E}|^2, \qquad (2)$$

where the integration in the numerator and denominator is over the cross section of the metal and the

 

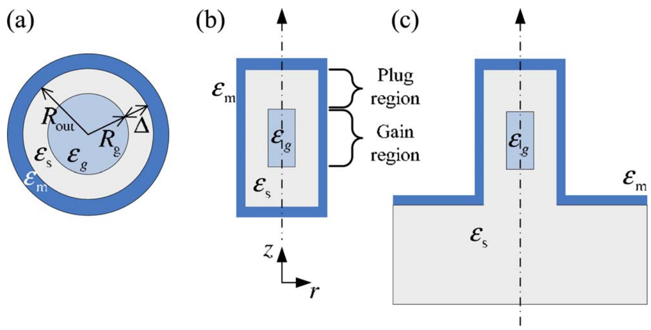


Fig. 1. (Color online) (a) Cross section of the metal-coated composite gain waveguide. (b) Cylindrical closed 3D resonator. (c) Cylindrical open 3D resonator.

gain medium, respectively. The threshold gain for each propagation mode may be found by imposing $\mathrm{Im}\{\beta\}=0$ in the dispersion relation and then finding the solutions in the plane of $(\mathrm{Re}\{\beta\},\varepsilon_g'')$, similarly to [10].

The effect of the shield layer on the $TE_{01}$ mode threshold gain is demonstrated in Fig. 2, where $\varepsilon_g''$ is plotted as a function of the shield thickness $\Delta$ for a given radius $R_{out}=300$ nm [Fig. 2(a)] and $R_{out}=460$ nm [Fig. 2(b)]. In the simulations we assume a wavelength of $\lambda=1550$ nm, $\varepsilon_g'=12.5$ corresponding to InGaAsP gain medium $\varepsilon_s=2.1$ for a $SiO_2$ shield layer, and $\varepsilon_m=-95.9-j11.0$ for a gold coating [11]. The rapid field decay in the gold layer permits us to assume that the metal extends to infinity, whereas in reality a coating layer of 100 nm would suffice. As the shield thickness increases, a lower percentage of the field penetrates into the metal, reducing the losses. On the other hand, the gain material occupies less of the CGW volume, which means that a higher gain is required to compensate for the dissipation losses in the metal. The trade-off between these two processes results in an optimal point in which the threshold gain is minimal. This typical behavior of low-order modes is seen in Fig. 2 for the $TE_{01}$ mode. For $R_{out}=300$ nm, the improvement of the threshold gain from the $\Delta=0$ (no shield layer) case is by a factor of 1.7, and for $R_{out}=460$ nm by a factor of 6.1.

For larger radii a lower threshold gain may be achieved, as shown in Fig. 2 and further emphasized in Fig. 3, where the minimal threshold gain $\varepsilon_g''$ is depicted as a function of $R_{out}$ for four low-order modes: $TM_{01}$, $TE_{01}$, $HE_{11}$, and $HE_{21}$. Having the highest con-

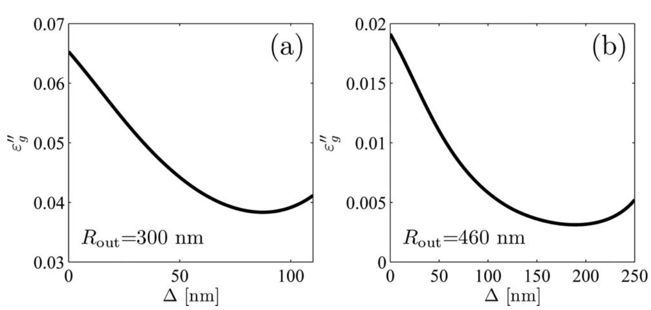


Fig. 2. Threshold gain $\varepsilon_g''$ as a function of the shield thickness $\Delta$ for the $TE_{01}$ mode. (a) $R_{out}=300$ nm. (b) $R_{out}=460$ nm.

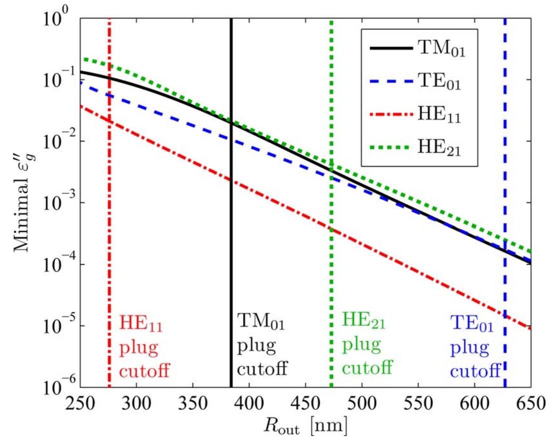


Fig. 3. (Color online) Minimal threshold gain as a function of $R_{out}$. The vertical lines show the cutoff of each mode in the 3D resonator plug region.

finement around the gain medium core, the $HE_{11}$ has the lowest threshold gain among the four modes. Generally, for small radii, the shield layer is less effective as it quickly gets the mode below cutoff. For large radii, the threshold gain is low, as the field penetration into the metal is small. The optimal shield layer thickness increases monotonically as a function of $R_{out}$. For the $TE_{01}$ mode, it ranges between 80 and 330 nm, for $R_{out}=250$ to 650 nm, respectively.

The role of the metal coating, which is important in the infinite CGW model, becomes even more crucial for creating a 3D resonator. As explained above, the CGW facets are terminated by plug regions, which are short metallic waveguides filled with $SiO_2$ as seen in Figs. 1(b) and 1(c), in an approach similar to that of Hill *et al.* [5]. The plug ensures strong confinement of the field in the gain region, provided that the mode residing in it is below cutoff, i.e., decaying exponentially in the $z$ direction.

For the plug region waveguide, the cutoff is not clearly defined since the modes are significantly different than those of the perfect conducting cylinder waveguide [12]. A reasonable definition for the cutoff is the $R_{out}$ whose $\beta$ is closest to the origin on the complex $\beta$ plane. That cutoff is shown for each one of the modes of Fig. 3 by the vertical lines, providing a qualitative tool for choosing an operation mode for the entire 3D structure, as the chosen radius needs to be to the left of the vertical line corresponding to the operation mode. The smaller the device radius compared to the cutoff radius, the stronger the decay in the plug; consequently, the threshold gain is lower. While the $HE_{11}$ mode achieves the lowest threshold gain for a given $R_{out}$, its cutoff in the plug region is at a small radius; working below this cutoff entails a relatively high threshold gain. It is therefore seen that the $TE_{01}$ mode, which has the highest cutoff of the shown modes, is favorable. The result is having a larger $R_{out}$ but a significantly lower threshold gain. Another advantage of the $TE_{01}$ is that this mode in the gain region couples only to symmetric TE modes in the plug region, whereas $m>0$ modes are hybrid and may couple to all modes with the same azimuthal index.

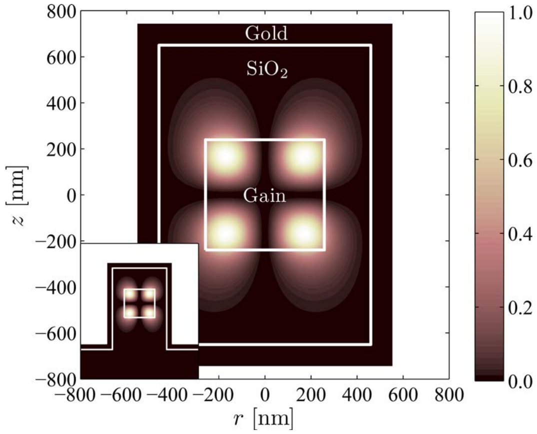


Fig. 4. (Color online) Cross section of a closed cylindrical 3D subwavelength laser resonator. The electric field intensity $|\vec{E}|^2$ normalized to its maximal value of the $TE_{012}$ mode is shown. The inset shows a similar open structure.

Using the CGW model at the optimal point of Fig. 2(b) as a starting point, a 3D closed resonator with $R_{out}=460$, and 100 nm thick gold coating was designed for the $TE_{012}$ mode. 3D finite element method (FEM) simulation results of the electric field intensity $|\vec{E}|^2$ normalized to its maximal value are shown in Fig. 4. The overall height of the resonator is 1500 nm, and the overall diameter is 1120 nm, making it smaller than the vacuum wavelength in all three dimensions. The resonance was fine-tuned to a wavelength of 1550 nm by setting the gain cylinder height to be about 480 nm and the shield layer thickness to about 200 nm, which is close to the 190 nm predicted by the CGW model. The threshold gain, however, is in less agreement with the CGW model; the value for the 3D resonator is $\varepsilon_g'' \simeq 0.011$, which corresponds to about $130\ \mathrm{cm}^{-1}$, whereas the CGW model gives about $36\ \mathrm{cm}^{-1}$. This discrepancy is due to the losses occurring in the plug region and the mode deformation at the interfaces between the plug and gain regions, two effects that are not taken into account in the CGW model. Obviously, the longer the resonator, the more accurately the CGW model describes the behavior in the gain region. For instance, a longer resonator with the same radius designed for the $TE_{013}$ mode has a threshold gain of about $95\ \mathrm{cm}^{-1}$.

If the structure shown in Fig. 4 is designed with no shield layer in the gain region, but with the same overall radius and height, then the resulting threshold gain is about $420\ \mathrm{cm}^{-1}$. The gain that may be achieved at room temperature by optical pumping of bulk InGaAsP is about $200\ \mathrm{cm}^{-1}$ [13]. It is therefore evident that the shield layer that lowers the threshold gain from 420 to $130\ \mathrm{cm}^{-1}$ is crucial to enable lasing at room temperature. Slightly modifying the structure for the open configuration, as shown in the inset of Fig. 4, the field distribution remains nearly unchanged and the threshold gain increases only to about $145\ \mathrm{cm}^{-1}$ owing to the radiation losses. The quality factor of this open resonator without gain is $Q \simeq 1125$, whereas the values for the other 3D structures with a shield layer discussed above are even higher. Finally, we note that for electrical pumping, considerably higher gains may be reached [14], so that the structure, with appropriate changes, is expected to be even further reduced in size.

In conclusion, we introduced and analyzed the effect of a low index shield layer between the gain medium and the metal coating of a gain waveguide and a 3D laser resonator. We showed that the shield layer in the gain waveguide has an optimal thickness for which the threshold gain to compensate for losses is minimal. The gain waveguide results were used to design a novel 3D resonator that is smaller than the vacuum wavelength of the emitted light in all three dimensions and has a sufficiently low threshold gain to allow lasing at room temperature.

This work is partially supported by the Defense Advanced Research Projects Agency, the U.S. Army Research Office, and the National Science Foundation.

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