Influence of surrounded metallic layers on whispering-gallery modes in circular microresonators

Q. F. Yao, Y. Z. Huang, X. M. Lv, J. D. Lin, and L. X. Zou
State Key Laboratory on Integrated Optoelectronics, Institute of Semiconductors,
Chinese Academy of Sciences, PO Box 912, Beijing 100083, China.
yzhuang@semi.ac.cn

Abstract—**Influences of surrounded metallic layers (Au, Al, Ag, Cu, and Ti) on whispering-gallery modes (WGMs) are numerically investigated by solving eigenvalue equation for multiple-layer two dimensional circular microresonators. For TM modes, metal layer can provide good optical confinement as its thickness is larger than 0.03 µm. For TE modes, an isolation layer should be introduced to reduce the dissipation loss of metallic layers. Al and Ag layers can provide better optical confinement than Au layer, and Ti layer which is usually a layer of p-electrode will result in a large dissipation loss.**

I. INTRODUCTION

Microcavities confined by a metallic layer have recently attracted great interests. The metallic layer can provide strong optical confinement and be used to miniaturize the device size [1]. The introduction of a low refractive index layer between the metal layer and the resonator was investigated for triangle and square microresonators for reducing the dissipation loss [2, 3]. Ti/Pt/Au is usually used as p-electrode for semiconductor lasers. However, copper (Cu) and aluminum (Al) are widely used in microelectronic circuits. So it is interested to use Cu and Al as electrode materials for photonic integrated circuits. In this paper, the influences of different metal layers Au, Ag, Cu, Al, and Ti on mode characteristics are numerically investigated for circular microresonators. We first introduce the analytical solution for the circular resonator with multilayer structure, and then compare mode quality factors for microcircular resonators confined by different metallic layers and dielectric/metallic layers, respectively.

II. ANALYTICAL SOLUTION FOR MICROCIRCULAR RESONATOR WITH MULTILAYER STRUCTURE

The two dimensional microcircular resonator as shown in Fig. 1 is considered, which is consisted of the active layer, the isolation layer, the metallic layer and the external layer. In the cylindrical coordination system (r, φ), Maxwell equations can be reduced to the following Helmholtz equation:

$$\frac{\partial^2\psi_z}{\partial r^2}+\frac{1}{r}\frac{\partial\psi_z}{\partial r}+\frac{1}{r^2}\frac{\partial\psi_z}{\partial\varphi^2}+k^2\varepsilon_r\psi_z=0 \qquad (1)$$

where ψ_z is electric field E_z for TM modes or magnetic field H_z for TE modes in the z-direction, ω is the angular frequency, $k = \omega(\mu_0\varepsilon_0)^{1/2}$ is the vacuum wave number, and ε_r is the relative permittivity.

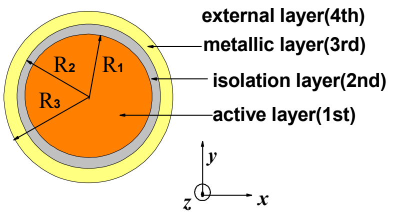

Fig. 1. Schematic diagram of a circular microresonator with multilayer structure.

The solutions of (1) are the combination of Bessel functions:

$$\psi_z(r,\phi)=\begin{cases} J_v(n_a kr)e^{\pm jv\varphi} & 0\le r\le R_1 \\ \left[A_1J_v(n_d kr)+B_1Y_v(n_d kr)\right]e^{\pm jv\varphi} & R_1\le r\le R_2 \\ \left[A_2I_v(n_m kr)+B_2K_v(n_m kr)\right]e^{\pm jv\varphi} & R_2\le r\le R_3 \\ CH_v^1(n_o kr)e^{\pm jv\varphi} & r\ge R_3 \end{cases} \qquad (2)$$

where v and l are azimuthal and radial mode numbers, respectively, J_v and Y_v are the v-order Bessel function of the first kind, I_v and K_v are the v-order imaginary argument Bessel function of the first kind and the second kind, and $H^1{}_v$ is the v-order Hankel functions of the first kind. n_a, n_d, in_m, n_o are the refractive index of the active layer, the isolation layer, the metal layer and the external layer, while the radius of the three interfaces are R_1, R_2 and R_3, respectively. For TE modes, the other two components E_r and E_φ are related to the z-directional magnetic field as:

$$E_r=\frac{-i}{kr\varepsilon_r}\frac{\partial H_z}{\partial\varphi}, \qquad E_\varphi=\frac{i}{k\varepsilon_r}\frac{\partial H_z}{\partial r}. \qquad (3)$$

According to the boundary conditions, i.e., H_z and E_φ continuous at the boundaries $r = R_1$, R_2 and R_3, we can induce eigenvalue equations. The complex angular frequency ω can be solved as the eigenvalue with help of Newton iteration, and mode wavelength, mode Q factor and mode field pattern can be calculated based on the mode frequency. In addition, TM modes can be solved by the similar processing.

In the following simulation, the active layer is taken to be InGaAsP or AlGaInAs with a refractive index of 3.2, and the isolation layer of silicon dioxide with a refractive index of 1.45.The dispersive model of metallic materials are refers to [4] with mode wavelengths around 1.5µm.

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III. SIMULATION RESULTS

Firstly, we consider the microcircular directly confined by the metallic layer. Mode quality factors versus the metallic layer thickness are plotted in Fig. 2 for (a) $TM_{10,1}$and (b) $TE_{9,1}$ modes in a circular microresonator with radius R_1 = 1μm, covered by Au, Al, Ag, Cu, and Ti, respectively. The mode wavelength is 1515 and 1524 nm for $TM_{10,1}$ and $TE_{9,1}$ in the circular microresonator in air without metal layer, respectively. For TM modes, mode *Q* factor firstly decreases with the increase of the metallic layer thickness due to the dissipation loss, but rapidly increases with the metallic layer thickness as the thickness is larger than 0.02~0.03 μm because of better confinement of the mode field pattern. The mode Q factor can be larger than 10^5 for the circular microresonator confined by Au, Al, Ag, or Cu layer with the thickness larger than 0.1μm. Al layer can even result in a higher mode *Q* factor. The metallic layers induce a larger dissipation loss for $TE_{9,\ 1}$, and the largest mode Q factor is about 10^3 in Fig. 2(b). Furthermore, the results show that Ti layer, which is usually used for improving the adhesion of p-electrode, results lowest mode *Q* factor.

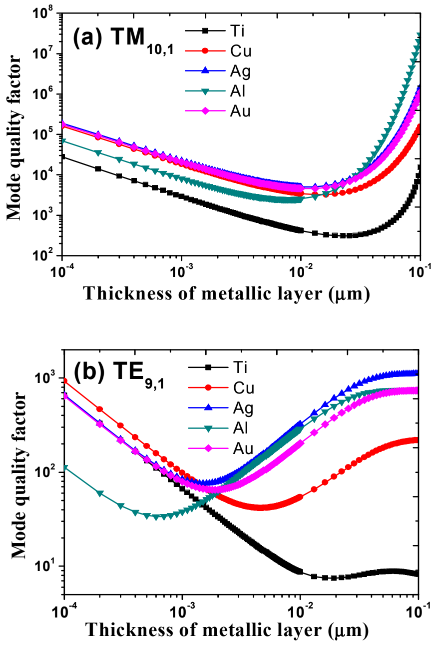

Fig. 2. Quality factors of $TM_{10,\ 1}$and $TE_{9,\ 1}$ modes as the function of the thickness of different confinement metal

To reduce the dissipation loss for TE modes, an isolation layer is introduced between the active layer and the metallic layer. The *Q* factor of $TE_{9,1}$ mode is plotted in Fig. 3(a) as the function of the thickness of the isolation layer for the circular microresonator confined by the isolation layer and 100 nm metallic layer. The isolation layer has an optimal thickness of about 550nm for highest *Q* factor, and the mode *Q* factor takes the highest value for microresonator covered by the silver layer. In addition, Al layer is a little better than Au layer for realizing high *Q* factor. In Fig. 3(b), we plot the field patterns for $TE_{9,1}$ in the circular microresonator with the gold layer of 100 nm and the isolation layer of 0, 500 and 900 nm, respectively. At the isolation layer thickness of 500 nm, the mode field pattern is a mixture of $TE_{9,1}$ and $TE_{9,2}$ due to mode coupling, which results in the decrease of mode *Q* factor with the increase of the isolation layer thickness. In addition, the mode field pattern is mainly located in the isolation layer at the thickness of 900 nm.

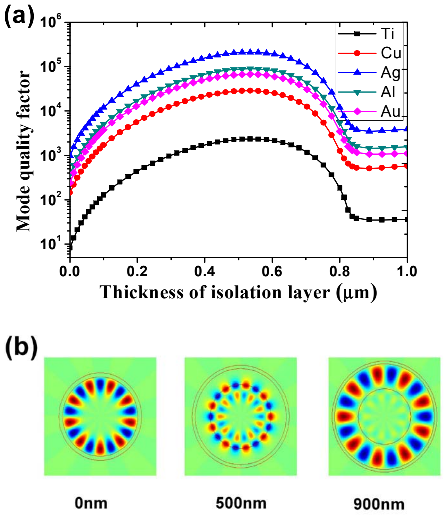

Fig. 3(a) Q factors of $TE_{9,\ 1}$ mode versus the thickness of isolation layer with different metallic confinement and (b) the mode field patterns with the isolation of 0, 500 and 900nm

IV. CONCLUSSION

We compare mode quality factors for whispering-gallery modes in circular microresonator confined by different metallic materials based on analytical solutions. The results show that silver and aluminum layer can provide better optical confinement than gold layer. The titanium layer usually used in p-electrode will greatly reduce mode quality factor.

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REFERENCES

[1] M. T. Hill, Y. S. Oei, B. Smalbrugge, Y. Zhu, T. De Vries, P. J. Van Veldhoven, F. W. M. Van Otten, T. J. Eijkemans, J. P. Turkiewicz, H. De Waardt, E. J. Geluk, S. H. Kwon, Y. H. Lee, R. Notzel, and M. K. Smit, “Lasing in metallic-coated nanocavities,” *Nature Photonics*, vol.1, pp.589-594, 2007. .

[2] Y. D. Yang, Y. Z. Huang, and S. J. Wang, “Mode analysis for equilateral-triangle-resonator microlasers with metal confinement layers,” *IEEE J. Quantum Electron.*, 45, pp. 1529-1536, Dec. 2009.

[3] K. J. Che, Y. D. Yang, and Y. Z. Huang, “mode characteristics for square resonators with a metal confinement Layer,” *IEEE J. Quantum Electron.*, 46, pp. 414-420, Mar. 2010.

[4] E. D. Palik, handbook of optical constants of solid, 1st ed, Boston: academic press, 1985.