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Erbium-Based Plasmonic-Assisted Vertical Emitter

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Abstract: Erbium-based plasmonic-assisted vertical emitters at telecommunication wavelengths have been investigated. We show that net gain and array of lasers are achievable.

Introduction

The use of plasmonics mixed with active photonic materials has been found to be promising due to the fact that the gain experienced through the emission of a gain medium is capable of counteracting the high attenuation of the electromagnetic wave. Also, positive net gain has been shown to be possible over macroscopic distances in a dielectric–metal–dielectric plasmonic waveguide, where the gain has been provided by an optically pumped layer of fluorescent conjugated polymer (known to have very large emission cross sections) adjacent to the metal surface [1]. A direct measurement of gain in propagating plasmons using the long-range surface plasmon–polariton supported by a symmetric metal stripe waveguide that incorporates optically pumped dye molecules in solution as the gain medium has also been shown [2]. Similarly, experimental evidence of stimulated emission of surface plasmon polaritons at telecom wavelengths (1532 nm) with erbium doped phosphate glass as a gain medium has been reported in [3]. Room-temperature pulsed laser emission from optically pumped metallo-dielectric cavities has been shown in [4]. Lasing in metal-insulator-metal waveguides filled with electrically pumped semiconductor cores has been reported in [5]. In this paper, we propose a dielectric vertical emitter consisting of an erbium doped active material layer sandwiched between two metallic layers. We use the metal layers for two purposes: (i) guide the plasmonic pump mode (mainly confined in the erbium layer) that has the role of exciting the active material; and (ii) act as mirrors in the vertical *z* direction to form a cavity resonating at 1532 nm. We employ the transverse resonance method [6] to compute the modes in the structure, and we focus on even (with respect to the *x* polarized electric field) TM modes. Such structures can be promising candidates for dielectric based vertical emitters.

Design of the vertical emitter

The proposed structure to achieve vertical emission at 1532 nm is illustrated in Fig. 1. The structure is assumed to be infinitely extended in the *xy* plane. It is a multi-layered structure made of two semi-infinite layers with refractive index n_u and n_b (for simplicity, here $n_u = n_b = 1$, or free space), two lossy metal layers (here made of silver, modeled by Drude model, with the parameters taken from [7]) of thickness d_m and refractive index n_m, and an active material doped layer (here erbium doped alumina) with thickness d_g and refractive index n_g (equal to 1.6 in absence of pumping). The erbium doped alumina layer is modeled as a three level system [8], where the pump wavelength is at 521 nm and the emission wavelength is at 1532 nm. From the classical theory, the steady state Er^{3+} concentrations at each energy level can be defined as [8]

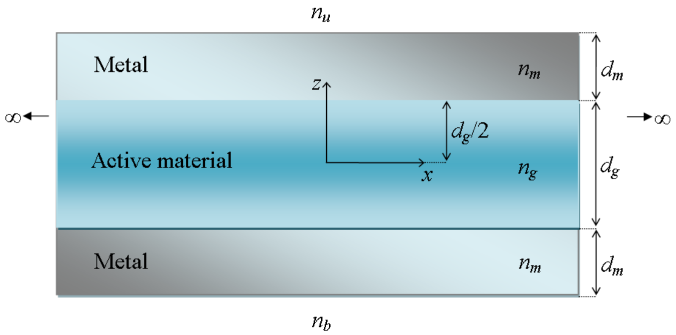

Fig. 1. Lateral view of the proposed structure.

$$N_1 = \frac{W_{31} + \Gamma/\tau_{32}}{W_{13}} N_3 \qquad N_2 = \frac{\Gamma \tau_{21}}{\tau_{32}} N_3 \qquad N_3 = \frac{N_t}{\left[\left(W_{31} + \Gamma/\tau_{32}\right)/W_{13} + \left(\Gamma \tau_{21}/\tau_{32}\right) + 1\right]} \tag{1}$$

where $N_t = 5\times10^{20}\ \text{cm}^{-3}$ is the total erbium concentration, and N_1, N_2, and N_3 are the Er^{3+} concentrations in the energy levels $^4\text{I}_{15/2}$, $^4\text{I}_{13/2}$, and $^2\text{H}_{11/2}$, respectively [9]. Only a percentage Γ (approximately 90%) of Er^{3+} ions is estimated to reach level $^4\text{I}_{13/2}$ from level $^2\text{H}_{11/2}$ due to weak emission intensity at intermediate levels [10]. The $^4\text{I}_{13/2}$ state lifetime is $\tau_{21} = 7.8$ ms and the decay time from $^2\text{H}_{11/2}$ to $^4\text{I}_{13/2}$ is $\tau_{32} = 37\ \mu\text{s}$ [9]. The transition rates W_{31} and W_{13} are assumed to be equal (i.e., no degeneracy) and their expression has been taken from equation (75) in [8]. The pump absorption cross section is $\sigma_{\text{abs}} = 27.6\times10^{-21}\ \text{cm}^2$, with a linewidth $\Delta\lambda_{\text{abs}} = 20$ nm; the signal emission cross section is $\sigma_{\text{em}} = 5.7\times10^{-21}\ \text{cm}^2$, with a linewidth $\Delta\lambda_{\text{em}} = 40$ nm [9-10]. The shape of the emission and

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absorption cross sections with respect to frequency is assumed to be homogeneously broadened, and Lorentzian. From the cross sections, we retrieve the imaginary part of the refractive index n_g in presence of pumping, and then we apply Kramers-Kronig relations to compute the variation of its real part to have a causal and physical system. The field reflectivity (R) of a silver mirror with respect to its thickness d_m is shown in Fig. 2. Reflectivity is 99.78%, 99.5% and 99.35% when $d_m = 40$ nm, 50 nm and 80 nm, respectively, and it remains almost constant to 99.34% for increasing thickness d_m. Here, $d_m = 100$ nm is selected since a minimum $d_m = 80$ nm is needed to guide a pump mode in the erbium region (side excitation) to excite the Er^{3+} ions. The silver layers are mirrors in the vertical z direction so that a mode resonating without transverse phasing in the cavity at 1532 nm could be excited, thus allowing for vertical emission. Therefore, erbium layer thickness d_g is optimized to achieve a net gain. To verify this condition, we compute one round trip gain inside the cavity, and see whether or not it is able to counteract completely metal losses. The net gain, in first approximation, can be computed as

$$G = e^{2\Delta N \sigma_{\mathrm{em}} d_g} R^4 \qquad (2)$$

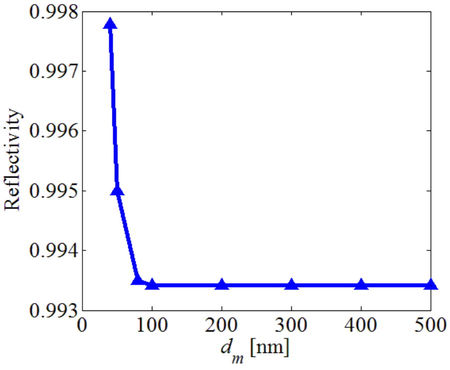

Fig. 2. Silver reflectivity versus thickness d_m .

where $\exp(2\Delta N \sigma_{\mathrm{em}} d_g)$ represents the small signal power gain experienced in a round trip in the cavity ($\Delta N = N_2 - N_1$ is the population inversion), and R^4 represents the power loss due to the two silver mirrors. A net gain is achieved when $G \geq 1$. The curves shown in Fig. 3 are based on a pump excitation accounting, for simplicity, for a single mode with magnitude of the electric field $|\mathbf{E}| \approx 0.65$ V/m at z = 0. It can be observed from Fig. 3(a) that net gain ($G \approx 1.055$) can be achieved in the cavity with thickness $d_g = 80$ μm, and the population inversion versus z in this case is reported in Fig. 3(b) (only the portion from z = 0 to z = 2 μm is shown for illustration). Multiple pump-excited modes are supposed to create a more uniform population inversion profile.

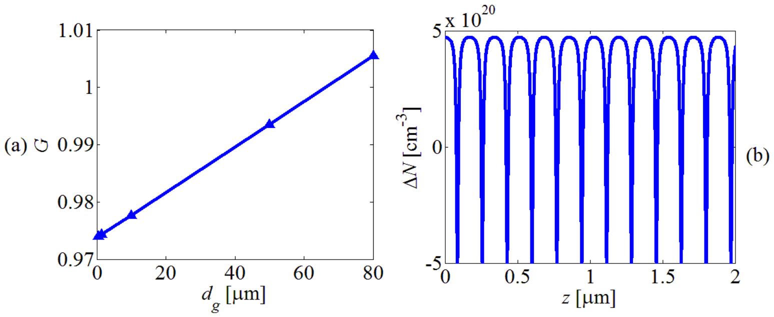

Fig. 3. (a) G versus thickness d_g . (b) ΔN (standing wave pattern) to achieve net gain for $d_g = 80$ μm (only portion from $z = 0$ to $z = 2$ μm).

Conclusion

We have shown the possibility of vertical emission through an erbium-based plasmonic-assisted structure. Optimized structures to get independent vertical emitters will be proposed in future studies. Also, other active materials may be used instead of erbium to reduce the thickness d_g needed to achieve net gain.

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References

[1] M.C. Gather *et. al*, “Net optical gain in a plasmonic waveguide embedded in a fluorescent polymer,” *Nature Photon.*, **4**, 457-461 (2010).
[2] I. De Leon and P. Berini, “Amplification of long-range surface plasmons by a dipolar gain medium,” *Nature Photon.*, **4**, 382-387 (2010).
[3] M. Ambati *et. al*, “Observation of stimulated emission of surface plasmon polariton,” *Nano Lett.*, **4**, 3998-4001 (2008).
[4] M.P. Nezhad *et. al*, “Room-temperature subwavelength metallo-dielectric lasers,” *Nature Photon.*, **4**, 395-399 (2010).
[5] M.T. Hill *et. al*, “Lasing in metal-insulator-metal sub-wavelength plasmonic waveguides,” *Opt. Express*, **17**, 13, 11107-11112 (2009).
[6] L. B. Felsen and N. Marcuvitz, *Radiation and Scattering of Waves* (IEEE Press, New York, 1994).
[7] A.L. Fructos *et. al*, “Characterization of complex plasmonic modes in two-dimensional periodic arrays of metal nanospheres,” *J. Opt. Soc. Am. B*, **28**, 6, 1446-1458 (2011).
[8] A.E. Sigman, *Lasers* (University Science Books, Mill Valley, 1986), Chapter 4.
[9] C. Strohhofer and A. Polman , “Absorption and emission spectroscopy in Er^{3+}-Yb^{3+} doped aluminum oxide waveguides”, *Opt. Materials*, **21**, 705-712 (2003).
[10] J.R. Lincoln *et. al*, “Spectroscopic evaluation of the vibrational coupling of Er^{3+} ions in phospho-aluminosilicate fibres and an explanation of compositional variations in Er-Yb 1.5 μm amplifier performance”, *J. Lumin.*, **60-61**, 204-207 (1994).