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Practicality of compensating the loss in the plasmonic waveguides using semiconductor gain medium

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We consider the issue of compensating the loss in plasmonic waveguides with semiconductor gain material and show that, independent of specific geometry, full loss compensation in plasmonic waveguides with significantly sub-wavelength light confinement (less than λ/4n) requires current density well in excess of 100 kA/cm^2. This high current density is attributed to the unavoidable shortening of recombination time caused by the Purcell effect inherent to sub-wavelength confinement. Consequently, an injection-pumped plasmonic laser that is truly sub-wavelength in all three dimensions ("spaser") would have threshold current densities that are hard to obtain in any conceivable semiconductor device. © *2012 American Institute of Physics*. [doi:10.1063/1.3673849]

Recent years have seen steadily rising interest in on-chip optical interconnects (OIs) capable of transmitting vast quantities of data over short distances more efficiently than metal conductors. In order to become practical, alternative OI's should not only have a large throughput but also be energy efficient, compact (not to consume valuable on-chip real estate), and compatible with existing fabrication (i.e., typically CMOS) techniques. Most research thus far has been concentrated in the field of silicon photonics where low-loss Si on SiO_2 waveguides, detectors, and modulators have been developed.[1] However, the dimensions of dielectric waveguides (hundreds of nm) are large by the standards of electronics. That is why in the last decade a potentially viable alternative to all-dielectric technology, called nanoplasmonics, has emerged.[2] In contrast to conventional waveguides, the optical field in the plasmonic waveguide is confined near the metal/dielectric interface or between two such interfaces. Besides convenience of using the same metal layer to guide both electrical and optical signals, the salient feature of plasmonics is that the light of wavelength λ can be confined in plasmonic waveguide on a substantially smaller scale than the $\lambda/2\,n_s$ scale on which it can be confined in the dielectric, or, as is the case here, in a semiconductor with refractive index $n_s = \sqrt{\varepsilon_s}$.

To illustrate the potentially advantageous features of plasmonic waveguides, consider the one in Fig. 1(a) in which the electric field of the surface plasmon-polariton (SPP) mode $E_z(z)\exp(j(k_x x - \omega t)$ is propagating along the interface with the in-plane wave-vector k_x while exponentially decaying both inside the semiconductor as $E_{zs}(z) \sim \exp(-q_s z)$ and inside the metal, $E_{zm}(z) \sim \exp(q_m z)$ such that $k_x^2 - q_{s,m}^2 = k_s^2 = \varepsilon_{s,m}\omega^2/c^2$. The in-plane wave-vector can be found from the SPP dispersion relationship $k_x^2(\omega) = k_s^2\varepsilon_m/(\varepsilon_m + \varepsilon_s)$ where $\varepsilon_m < 0$ is the metal's relative permittivity that in the Drude approximation can be written as $\varepsilon_m(\omega) = 1 - \omega_p^2/(\omega^2 + j\omega\gamma)$. When the frequency of light ω approaches the surface plasmon frequency $\omega_{sp} = \omega_p/(\varepsilon_s + 1)^{1/2}$ both k_x and q_s become large. Large k_x indicates that the effective wavelength of light becomes shorter which allows plasmonic waveguides to be narrower and have sharper turns than their dielectric counterparts. This effect can be quantitatively expressed as the effective (relative to the plane wave in the semiconductor) index $n_{eff} = k_x/k_s > 1$. Thus, the in-plane dimensions of the waveguides (such as strip width, turning radius, or cavity length for the laser) all scale down as n_{eff}^{-1}. A large q_x indicates tight confinement that can be quantified as small effective thickness $d_{eff} = \ln(10)k_s/4\pi q_s$, where 90% of the energy is contained (normalized to the wavelength in the semiconductor). Calculations show that $n_{eff} > 3$ and $d_{eff} < 0.1$ are within the grasp, thus opening exciting possibilities for miniaturized optical elements.[3]

Unfortunately, it has been also long realized that plasmonic waveguides always exhibit losses γ larger than dielectric ones due to the absorption in the metal, with values as high as $12.3 \times 10^{13}\,s^{-1}$ in gold and $3.6 \times 10^{13}\,s^{-1}$ in silver.[4] Therefore, a two pronged effort of dealing with loss has evolved. The first effort included developing designs with reduced penetration of light into the metal, including long-range plasmonic waveguides, but it was also quickly discovered that the reduced loss usually was accompanied by reduced confinement, although this discovery has not dampened the enthusiasm for new shapes. The second effort, which appears entirely reasonable, is to use a gain medium to compensate the metal loss, thus not only developing loss-free devices but also sub-wavelength sources of coherent radiation ("spasers"). Besides a large number of theoretical works,[5–7] there has been experimental progress[8] including demonstration of miniature lasers,[9–13] albeit always operating in pulse mode *and, what is important, always having dimensions larger than half wavelength in the material along at least one direction*. Surprisingly, a consistent theoretical analysis has never been performed to determine the threshold of a laser, or to find the power density required to compensate the loss in the tightly confining plasmonic waveguide. In this work, we provide this analysis for the most (and possibly the only) practically feasible scheme with semiconductor gain medium with injection pumping and arrive at two conclusions: *(1) for the tightly confining sub-wavelength plasmonic waveguides, the effective modal loss γ_{eff} is always on*

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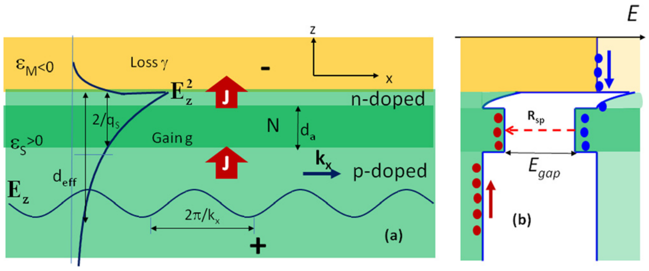

FIG. 1. (Color online) (a) Fields in the plasmonic waveguide on a metal-semiconductor interface. (b) Energy band-structure of the injection-pumped semiconductor.

the order of the metal loss γ independent of specific geometry; (2) the radiative time shortening caused by the Purcell effect raises the transparency current density to the unsustainable levels of 100's and 1000's of kA/cm^2 which makes both full loss compensation and "spasing" dubious propositions.

Consider the loss-compensating scheme in Fig. 1(b) in which an active layer d_a of semiconductor material with bandgap corresponding to SPP frequency ω sandwiched in a double-heterostructure of a wider bandgap material. We consider two material systems—the first one is for the longer wavelengths using Au and $In_xGa_{1-x}As_yP_{1-y}$ and the second, for the shorter wavelength using Ag and $In_xGa_{1-x}N_yAs_{1-y}$. In this analysis, we assume the best case scenario that all these quaternary semiconductors with wide ranges of band gaps can be grown. We shall use d_{eff} as a parameter in all our calculations, but remember that for a given material system, each d_{eff} corresponds to a particular wavelength as shown by the scale at the bottom of Fig. 2.

First of all, let us estimate the modal loss γ_{eff} as a function of confinement. Even before performing the exact calculations, a simple conclusion can be made from energy conservation arguments. Following Maxwell's equation, $\nabla \times \boldsymbol{H} = \varepsilon_0\varepsilon_S \partial \boldsymbol{E}/\partial \boldsymbol{t}$, one can find the relation between magnetic and electric field magnitudes as $H \sim (\omega/k_x)\varepsilon_0\varepsilon_S E$ indicating that the ratio of the energy stored in the magnetic form when the phase of the electric field is 90° (or 270°) to the energy stored in electrostatic form when the phase of the electric field is 0° (or 180°) is $\mu_0 H^2/\varepsilon_0\varepsilon_S E^2 \sim 1/n_{eff}^2 < 1$. Therefore, the remaining energy has to be stored in the form of kinetic motion of free electrons in the metal dissipating at the rate of 2γ, and we obtain for modal energy loss $\gamma_{eff} = \gamma(1 - n_{eff}^{-2})$ considering the fact that the energy is stored in kinetic form for only half of the period. The results of exact calculations showing both n_{eff} (Fig. 2(a)) and γ_{eff} (Fig. 2(b)) as functions of d_{eff} confirm these assumptions (which have been made without restriction to any specific geometry) and indicate that, independent of the geometry, the modal loss is always commensurate with the metal loss once n_{eff} reaches a relatively modest value of 1.5. (It should be noted though that these results are no longer valid in far infrared (IR) and THz regimes not considered here[14]).

Let us now see what transparency carrier density N_{tr} is required to compensate this modal loss. The modal gain per second can be found as $g(\omega) = B\sqrt{\hbar\omega - E_{gap}}(f_c(\omega) - f_v(\omega))\Gamma$ where f_c and f_v are the carrier density-dependent Fermi-factors in the conduction and valence bands,

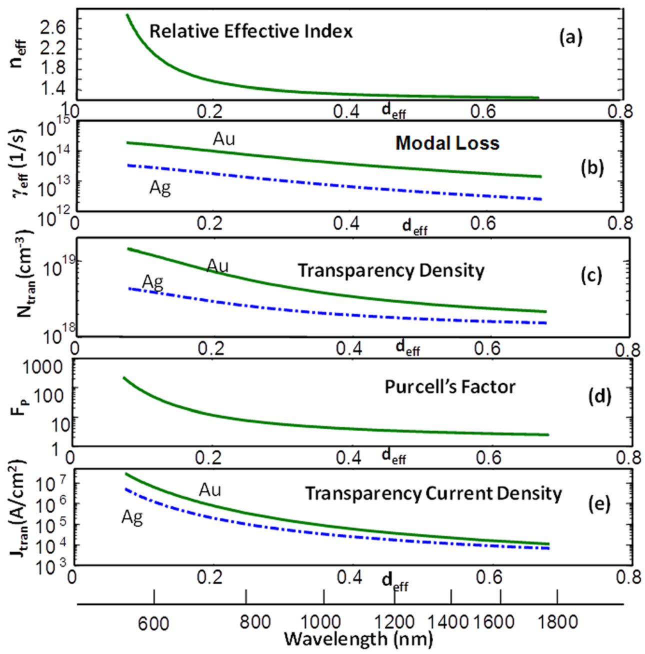

FIG. 2. (Color online) Characteristics of loss-compensated Au/$In_xGa_{1-x}As_yP_{1-y}$ (solid curves) Ag/$In_xGa_{1-x}N_yAs_{1-y}$ (dashed curves) plasmonic waveguides as functions of effective thickness d_{eff} and corresponding wavelength λ (a) n_{eff}, (b) γ_{eff}, (c) N_{ran}, (d) F_P, and (e) J_{tran}.

$\Gamma = 2q_s\int_0^{d_a} e^{-2q_s x}dx$ is the gain confinement factor, and the stimulated emission coefficient B that depends on frequency, effective masses, and the oscillator strength[15] and varies from $6.5\times10^{14}\,s^{-1}\,eV^{-1/2}$ for InGaAs at 1500 nm to $13.5\times10^{14}\,s^{-1}\,eV^{-1/2}$ for InGaN at 440 nm. It is sensible to choose $d_a = 1/2q_s$ to obtain $\Gamma = 0.63$. The transparency carrier density N_{tran} at which $g(\omega) = \gamma_{eff}(\omega)$ as a function of d_{eff} is shown in Fig. 2(c) and appears to be quite reasonable 10^{18}–$10^{19}\,cm^{-3}$ mostly thanks to this large Γ. But by itself, N_{tran} does not establish the feasibility of a device: what is important is the current density required to achieve transparency and determined by the spontaneous recombination rate R_{sp}, which can be found as $J_{tran} = 4ed_a\varepsilon_s^{3/2}c^{-1}\lambda^{-2}BF_P \int_{E_{gap}}^{\infty}\sqrt{\hbar\omega - E_{gap}}\,f_c(\omega)(1 - f_v(\omega))d\omega$, where $F_P = 1 + \pi\Gamma q_s k_x\omega(dk_x/d\omega)/k_s^3$ is the often overlooked Purcell's factor[16] related to the fact that the density of SPP states into which the spontaneous emission takes place is higher than in an unconfined semiconductor. Purcell's effect can be large due to confinement (q_s and k_x) and especially due to reduced in-plane group velocity $d\omega/dk_x$. It can be shown that Purcell's factor scales roughly as n_{eff}^5 as is indeed confirmed by exact calculations in Fig. 2(d).

It is the presence of Purcell's factor, normally responsible for such beneficial and useful effects as enhancement of fluorescence and Raman scattering that plays such a deleterious role here by raising the transparency current densities (Fig. 2(e)) in even modestly confined plasmonic waveguides with $d_{eff} < 0.25$ (half of the diffraction limit) to about 100 kA/cm^2 for silver waveguides and 300 kA/cm^2 for gold ones. These numbers are at least two orders of magnitude larger than the threshold current density in a typical high power double heterostructure semiconductor laser.[15] Notice that the value of J_{tran} is not influenced significantly by either

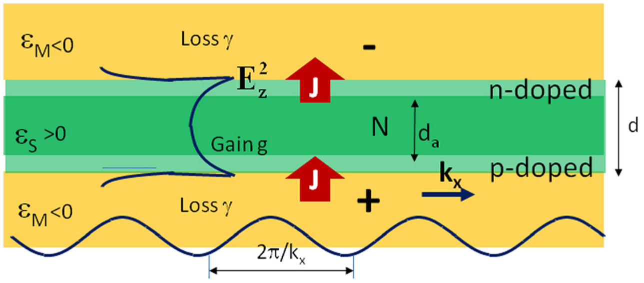

FIG. 3. (Color online) MSM waveguide with loss compensation.

the type of semiconductor used or by the confinement factor Γ because the probability of the spontaneous recombination (1st Einstein's coefficient) contains essentially all the parameters included in gain (2nd Einstein's' coefficient) multiplied by the density of photon states. Using a gain medium with multiple quantum wells and dots does not show significant reduction of J_{tran} and would only complicate the carrier transport. We have also performed calculations for lower temperatures and have shown that, for Ag waveguides with $d_{eff} = 0.25$, J_{tran} can be as low as 12 kA/cm^2 at 100 K and as small as 3 kA/cm^2 at 30 K, but even at these temperatures, the transparency current density increases dramatically with the effective index, reaching 1 mA/cm^2 for silver and 5 mA/cm^2 for gold even for a modest $n_{eff} = 2$, i.e., this huge increase in current density would only buy a four-fold decrease in the device surface area relative to the low loss all-dielectric structures.

One issue with a single strip plasmonic waveguide is the fact that large confinement is usually achieved at relatively short wavelengths where spontaneous recombination time is short. Therefore, one may consider metal-semiconductor-metal (MSM) waveguide shown in Fig. 3 where the light is always confined between two metal surfaces for any wavelength, including the important telecom wavelength $\lambda = 1550$ nm. The results of calculations are shown in Fig. 4 and they indicate that one can achieve loss compensation for the waveguide thickness d of about 100 nm, i.e., about $\lambda/4\,n_s$ with $J_{tran} \sim 40$ kA/cm^2 at room temperature—a definite improvement compared to the strip waveguide. However, at this tight vertical confinement, the lateral dimensions would still be determined by $n_{eff} \sim 1.6$, i.e., only 30% smaller than the dimensions achievable with metal-free waveguides, hardly enough to justify additional cost and complexity of using more than one metal layer. In order to achieve the transparency in a structure with both vertical and lateral dimensions less than $\lambda/4\,n_s$ ($n_{eff} > 2$), which in our view can be truly referred to sub-wavelength, the room temperature current density must exceed 100 kA/cm^2 (Fig. 4(e))—something barely achievable even in high power transistors. Such effective densities can be achieved in principle using optical pulsed pumping[8,17] but the practicality of such an arrangement, even leaving alone the power dissipation issues, is uncertain.

In conclusion, we have highlighted two important issues that need to be taken into account when considering loss compensation and lasing in semiconductor/plasmonic waveguides. These results are quite general, with a very weak dependence on either the geometry or gain material. First of all, when the confinement becomes substantially less than $\lambda/2$ n, the modal loss inescapably approaches that of the metal

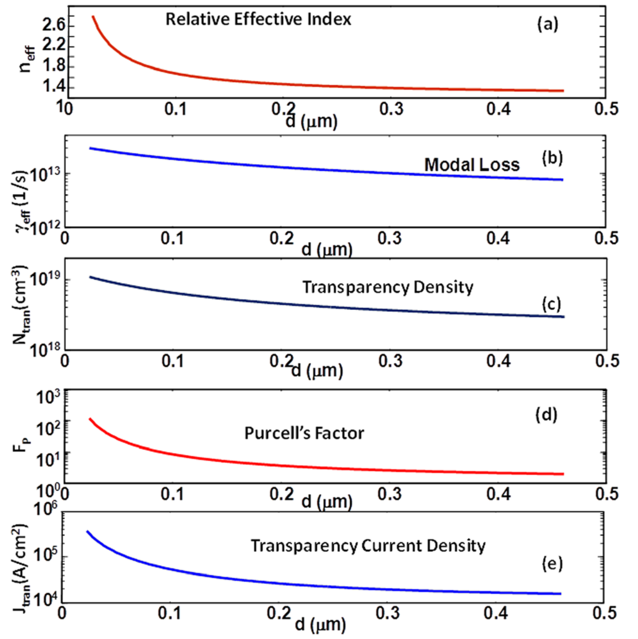

FIG. 4. (Color online) Characteristics of loss-compensated Ag/In$_{0.53}$Ga$_{0.47}$As/Ag plasmonic waveguide operating at $\lambda = 1550$ nm as functions of thickness (a) n_{eff}, (b) γ_{eff}, (c) N_{ran}, (d) F_P, and (e) J_{tran}.

itself, i.e., 10^{14} s^{-1}. Second, while the carrier density required to compensate this loss is not outrageously high, the recombination time gets shortened by orders of magnitude due to Purcell's effect (often overlooked yet inherent in tightly confined volumes). Therefore, the current densities required to achieve first, full compensation, and later, lasing threshold, become unsustainably high, leaving one with the choice of either sticking with all-dielectric waveguides, using long range plasmons[18,19] or their combination, so-called hybrid waveguides,[20] all with relatively weak confinement.

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