QD-PMMA nanocomposite plasmonic waveguides

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Abstract: In this work colloidal quantum dots (QD)-PMMA nanocomposites are proposed as a material able to compensate losses in surface plasmon polariton (SPP) propagating along a gold plasmonic waveguide. For this purpose geometrical parameters of the waveguides are optimized with the appropriate simulations prior to the fabrication of the structures. Then, a new method to measure the propagation length of the SPP is proposed to characterize the structures and to estimate the propagation length.

Introduction Nowadays there is a great concern of combining plasmonic waveguides with photonic technology. This is because the hybrid electromagnetic wave and charge surface state nature of the surface plasmon polaritons (SPP) [1] allows for unique properties like subwavelength confinement and strong electric field concentration, which could be used to miniaturize the final size of the device and reduce its power consumption in future electronic/photonic technology [2]. However, the propagation length (L_P) of SPPs is limited by the high ohmic losses in metals and. This limitation can be compensated by an appropriate design of the plasmonic waveguide. A first approach is to provide gain in the dielectric on top of the metal [3] that could amplify the SPP signal [4]. In addition, the propagation length can be increased by combining the SPP with dielectric waveguide modes [5], which usually exhibit small propagation losses. In this work a combination of both solutions is presented as a method to couple light into the SPP and to increase its L_p.

The active material proposed in this work consists of colloidal quantum dots (QD) embedded in an appropriate polymer (PMMA in our case). Such a nanocomposite is of great interest nowadays, because it combines the properties of the QDs (i.e., room temperature emission and tuning of the absorption/emission wavelengths by changing their size and composition [6]) with the technological feasibility provided by the polymer, (i.e., deposition by different solution processing methods and patterning by using either e-beam lithography or nanoimprint [7]). The use of QD-PMMA in photonics was demonstrated in Ref. 7 by using such a nanocomposite as the core of active planar waveguides. In addition, (PbS QDs)-PMMA films have already been used to compensate the losses of the SPP propagation at infrared wavelengths [8-9]. In this work (CdSe QDs)-PMMA/Au plasmonic waveguides deposited on a SiO_2/Si substrate (see Fig. 1a) are analyzed; the structures were carefully designed to optimize the light confinement in the metal together with low losses. The L_p of optical modes in the waveguide has been characterized by using a novel experimental method based on the use of a fiber tip that couples the input signal into SPP modes. An additional pump beam that is end-fire coupled into the plasmonic waveguides produces an enhancement of the SPP L_p.

Waveguide design. Figure 1a shows the structure of the CdSe-PMMA/Au plasmonic waveguides used in the present work. The Au was deposited by evaporation (30 nm thick) on a SiO_2/Si substrate (CEMAT Silicon S.A.) and the stripes (6 - 20 μm wide) by a standard lift-off process. The CdSe-PMMA nanocomposite is spin-coated by following the procedure developed in Ref.7. These plasmonic waveguides were optimized by solving the propagation constant of the guided modes with the transfer matrix method in a complex plane at the photoluminescence (PL) peak wavelength (600 nm), in a similar way as that previously reported in Ref. 10 for planar structures. The optimization consisted in achieving a maximum confinement and propagation length for the long range SPP (LR-SPP). In this way, a gold film around 30 nm thick is an appropriate trade-off between the LR-SPP confinement (increasing with thickness) and propagation length (decreasing with thickness), L_P, for which L_P = 11.7 μm and the mode confinement is around 10 % [10]. Figure 1c shows the effective refractive index of several optical modes and L_p of the LR-SPP mode as a function of the CdSe-PMMA nanocomposite thickness (lines in color and left axis). Here it is important to point out that the nanocomposite layer should ideally be thick enough to contain the whole evanescent tail of the TM fundamental mode. However, above a certain thickness ($d \approx 1100\ nm$) higher order hybrid TM modes

start to be guided and hence a thickness d=1 μm was fixed. Figure 1d depicts the LR-SPP mode confined in a stripe 6 μm wide.

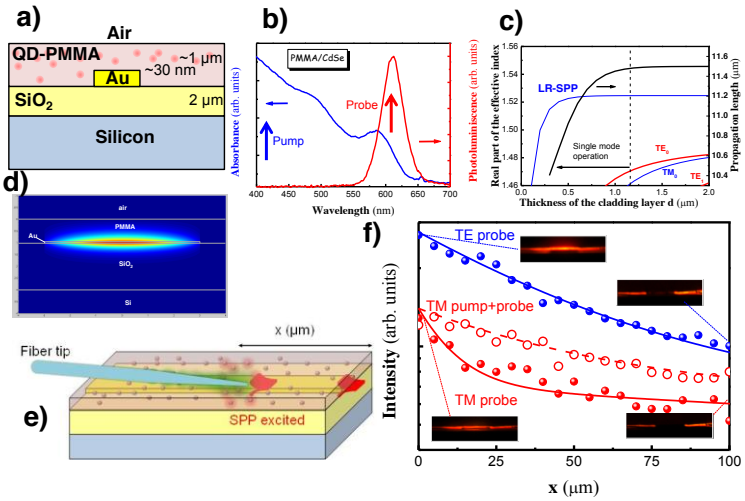

Fig. 1: a) Waveguide structure. b) Absorbance (blue line) and PL (red line) spectra of the CdSe-PMMA nanocomposite. c) Calculation of several propagating modes and propagation length in a planar structure as a function of the nanocomposite thickness. d) Simulation of the LR-SPP mode. e) Experimental set-up. f) Characterization of Lp in TE (blue) and TM (red) without (solid symbols and continuous lines) and with (hollow symbols and dashed line) end-fire coupled pumping laser. The pictures show the near field distribution in TE and TM at x=0 and x=100 μm.

Waveguide characterization. Plasmonic waveguides were characterized by exciting the PL of CdSe QDs at 533 nm with a fiber tip and recording the guided PL signal at the nearest waveguide edge, as illustrated in Fig. 1d. Figure 1f shows the signal intensity as a function of the distance between the fiber tip and the waveguide edge for TE and TM modes (blue and red solid symbols, respectively), which is fitted (continuous lines) by the sum of two exponential decays where L_P for both modes is deduced: $\sim A_1 e^{(-x/Lp1)} + A_2 e^{(-x/Lp2)}$. The shortest propagation length, L_{p1}, for TM mode corresponds to the LR-SPP and the best fit yields $L_{p1} = 11.1\ \mu m$, which is very close to the calculated value (11.4 μm, see Fig. 1c). The fit for the TE mode gives a longer L_p value (50 μm), given that this mode is centered at the dielectrics (QD-PMMA nanocomposite) and not at the metal (see pictures at x = 0 μm in Fig. 1f). The longest propagation length, L_{p2}, corresponds to the light travelling out of the metal stripe and hence is similar under both polarizations (see pictures at x=100 μm in Fig. 1f). The QD-PMMA film can be used to couple a pump beam by end-fire coupling of 404 nm laser (on the opposite face to that of detection) to compensate for the losses of the LR-SPP mode (red open symbols in Fig. 1f). Again, this experimental curve can be fitted by the same two exponential decay functions (dashed line) yielding a value for L_{p1} of around 35 μm.

Conclusions. Plasmonic waveguides based in a QD-PMMA nanocomposite are proposed. The structures are optimized to achieve optimum light confinement and low losses and are coupled to a photonic waveguide where a pump beam can be propagated with low losses. A novel experimental set-up based on a fiber tip is used to measure the LR-SPP propagation length. An enhancement of this propagation length by around 3 fold is demonstrated when PL of QDs in the nanocomposite is excited by end-fire coupling.

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References

1. S.A. Maier, *Plasmonics Fundamentals and Applications*, Ed., New York: Springer, (2007).
2. J. Leuthold *et al*., Optics and Photonics News, pp. 30-35, (2013).
3. P. Berini and I. De Leon, *Nature Photonics*, **6**, pp. 16-24, (2012).
4. M.C. Gather *et al*., *Nature Photonics*, **4**, pp. 457-461, (2010).
5. R.F. Oulton *et al*., *Nature Photonics*, **2**, pp. 496-500, (2008).
6. V.I. Klimov *et al*. ,Science, **28**, pp. 214-220, (2003).
7. I. Suárez *et al*., *Nanotechnology*, **22**, 435202, (2011).
8. J. Grandidier, *et al*., *Nanoletters*, **9**, pp. 2935-2939, (2009).
9. I.P. Radko *et al*., *Optics Express*, **18**, pp. 18633-18641, (2010).
10. I. Suárez *et al*., *ICTON Proceedings*, (2013).