Nano Scale Disruptive Silicon-Plasmonic Platform for Chip-to-Chip Interconnection

Demonstration of decision on optimized structures for plasmonic amplifiers

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Executive Summary

This document shall incorporate (all) rules procedures concerning the technical and administrative management of the project and is therefore to be updated on a regular basis. Please look at www.navolchi.eu regularly for the latest version.

Change Records

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1. Introduction

Surface plasmons (SP) are coherent oscillations of free electrons present at the boundary between a metal and a dielectric. Under appropriate conditions when SPs are exposed to a flow of visible or infrared light, they can be coupled to the incident photons leading to a hybrid electromagnetic-wave and charge-surface state known as surface plasmon polariton (SPP). In these conditions SPP can propagate along the interface showing unique properties as subwavelength confinement, strong near electromagnetic field enhancement or high sensitivity to the environment [1]. However, the ohmic losses of metals lead to a strong attenuation of the propagation length of SPP (see the illustration in figure 1a) and, in consequence, the potential applications of SPP based devices. Particularly, a good mode confinement, necessary to exploit the possibility of guiding light beyond the diffraction limit, is achieved using sufficiently thick metal layers. However, propagation losses of SPP increase with the thickness of the metal as well, so there is a trade-off between good mode confinement and low propagation losses [2]. This problem can be overcome by providing gain in the dielectric material adjacent to the metal, in such a way that absorption losses will be compensated and the SPP propagation length significantly increased, as exemplified in figure 1b. In literature different materials like dyes [3], fluorescent polymers [4], rare earths [5] and PbSe quantum dots (QDs) [6] have been proposed as gain media for wavelengths between 600 and 1500 nm.

In this project a novel material based on the incorporation of colloidal QDs in a polymer matrix is proposed as a dielectric medium to provide gain in plasmonic waveguides. This kind of nanocomposite (polymer + QDs) is useful because it combines the novel properties of colloidal quantum dots (temperature independent emission and colour tuning with the base material) with the technological feasibility of polymers (spin coating, UV photolithography, nanoimprint and e-beam lithographies, ...). In fact, the application of PMMA doped with CdSe QDs in the development of active dielectric waveguides has been already demonstrated at 600 nm [7]. Furthermore, wavelength tunability of the device (from 400 nm to more than 2 μm) can be achieved just by changing the chemical nature and size of the QDs, without modifying the fabrication conditions [8]. We thus propose the use of QD-PMMA (and QD-SU8) nanocomposites on gold films (and stripes for final devices) in order to provide gain to the SPP propagation, using a similar configuration as the one shown in figure 1. Target wavelengths in these milestone are in the telecom range, from 1.3 to 1.55 μm, feasible by using PbS QDs (whose synthesis and gain capabilities are summarized in MS17).

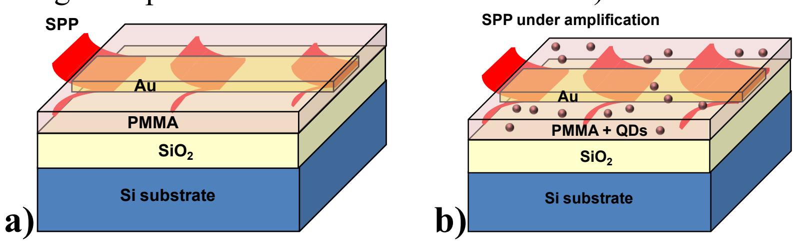

Figure 1. Illustration of SPP waveguiding without (a) and with amplification (b).

2. Planar SPP designs

The first considered design consisted of a gold layer deposited (by evaporation, for example) on a SiO_2/Si substrate and a nanocomposite (QD-PMMA) thin film is spin-coated onto the metal (figure 2a). In the second considered design the gold layer is sandwiched between two nanocomposite films. The thickness of the SiO_2 was fixed to 2 μm, whereas the thicknesses of the gold layer (t) and the nanocomposite films (d, d_1, d_2) are parameters to be optimized in the design. Of course, the concentration of QDs inside the polymer is another critical parameter that has to be properly studied. The analysis on both designs is considered without and with gain.

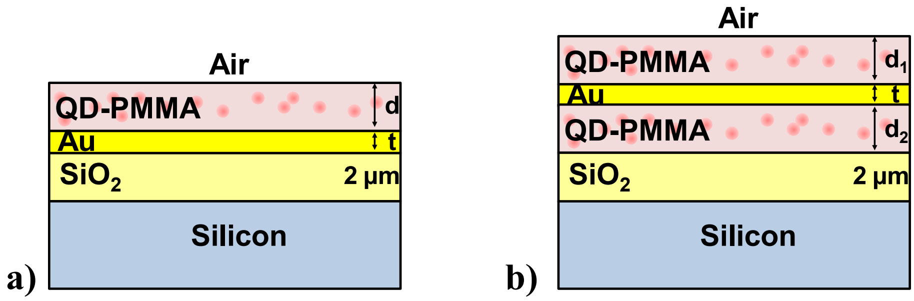

Figure 2. Designs of SPP amplifiers.

A. Influence of thickness of the gold layer (*t*)

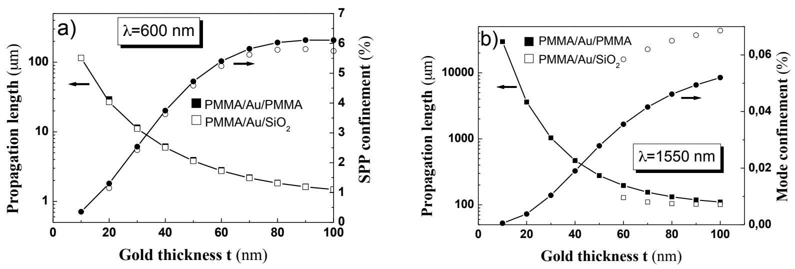

Figure 3. Propagation length and confinement factor as a function of the gold layer thickness for a) 600 m and b) 1550 nm.

The thickness of the gold layer implies a trade-off between mode confinement and propagation losses [2]. The thicker the Au layer, the better is the confinement of the long range SPP (LR-SPP) mode. However, thicker layers also imply a reduction in the propagation length due to the attenuation in the metal. Figure 3 plots the propagation length and the LR-SPP confinement as a function of the Au thickness for two different operating wavelengths: 600 (figure 3a) and 1550 nm (figure 3b). At short wavelengths (600 nm) the LR-SPP mode can achieve confinements up to 10-15 %, but the maximum propagation length is only around 100 μm. On the other side, the propagation length at 1550 nm can increase up to the mm range while the mode confinement is as low as 0.05 %. At 1.55 μm the asymmetric waveguide does not exhibit propagating modes for Au layers thinner than 50 nm, so this design was not considered at that wavelength. A thickness of the gold layer from 20 to 40 nm seems to be a good compromise between losses and confinement and hence a thickness of 30 nm has been fixed in the design and experiments. Figure 4a shows the intensity variation of the LR-SPP mode in the symmetric structure for both wavelengths using ***t = 30 nm***. The mode is centered in the gold with an exponential decay in the dielectric of around 1 and 9 μm at 600 (red line) and 1550 nm (black line), respectively.

B. Influence of thickness of the capping layer (*d*)

The top layer thickness will include the QDs that will provide gain in the SPP. Then it should be thick enough to contain the whole evanescent tail of the TM fundamental mode. However, above a certain thickness higher order modes start to be guided, influencing the behavior of the amplifier. These modes are hybrid (photonic-plasmonic) ones because they are mostly confined in the dielectric layers (PMMA or SiO_2). Figure 5 shows the real part of the effective refractive index of the TM modes (symbols) as a function of the cladding layer thickness (*d*) at 600 (figure 5a) and 1550 (figure 5b). The propagation length of the fundamental long range TM_0 mode is also included in these figures (continuous lines).

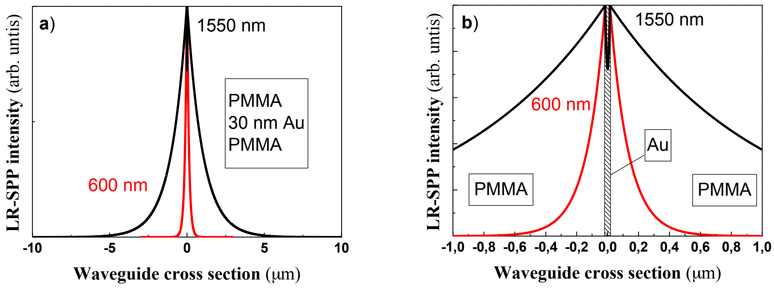

Figure 4. a) LR-SPP mode distribution at 600 nm (red) and 1550 (black). b) Zoom at the center of the structure.

The length of the evanescent field (calculated at the 99 % of the maximum) is about 550 nm (see a zoom in figure 4b at 600 nm). Therefore, the thickness of the cladding layer should be higher than this value in order to minimize losses. Indeed, this effect is translated as a decrease of the propagation length, as it is shown in figure 5a. It is also interesting to note that when the thickness of the layer is thicker than 700 nm the symmetric structure higher order TM modes appear that can affect the behavior of the waveguide. In the case of the asymmetric structure the TM_0 threshold increases up to 1.2 µm, making it possible to accomplish single mode propagation with lower losses. Since the symmetric and asymmetric structures give similar losses at **600 nm** the assymetric one with ***d* ≈ *1 µm*** seems to be the simplest optimal choice. At **1550 nm** the LR-SPP evanescent tail extends up to around 4.5 µm (figure 4a). However, such a thick cladding implies the propagation of four high order TM hybrid modes in the symmetric structure and ***d* = *2-3 µm*** seems to be the most appropriate choice.

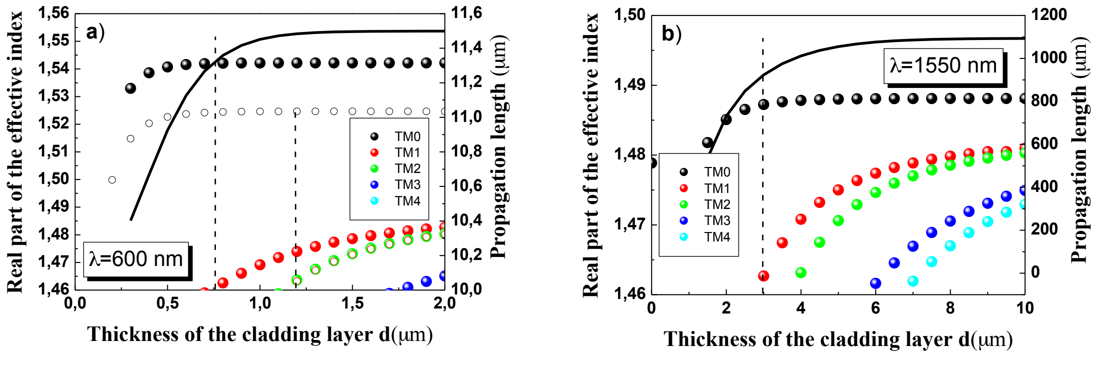

Figure 5. Real part of the effective refractive index (symbols) and propagation length (continuous line) of the fundamental mode as a function of the thickness of the cladding layer for 600 (a) and 1550 nm (b). Symmetric structures (figure 2b) were simulated with t = 30 nm and $d=d_1=d_2$. Open symbols correspond to the TM_0 and TM_1 modes in the corresponding asymmetric structure at 600 nm only. Vertical dashed lines indicate the appearance of new higher order TM modes.

C. Gain in the dielectric.

The gain material chosen in this work is based on semiconductor QDs embedded in PMMA. However the dispersion of the nanostructures in the polymer has a limitation due to reabsorption effects and roughness of the layers, and an optimum filling factor (volume fraction occupied by QDs), *ff*, of about ***ff~10***$^{-3}$ has been experimentally demonstrated for waveguiding applications [7]. It is worth to note here that the refractive index of the nanocomposite is only modified by about 1% with respect to the index of PMMA given that low concentration of QDs.

Table I summarizes the net gain to be provided by QDs to compensate losses totally (first column) and to achieve a net gain of 10 dB/cm (second column) in the symmetric structures discussed above. The cladding layer thicknesses were fixed to 1 and 3 µm for 600 and 1550 nm, respectively, and two cases, considering gain in the top or in both the top and bottom layers. Of course, QDs dispersed at both top and bottom layers reduce the gain in a factor two, approximately. It is interesting to note that the minimum material gain is similar in both symmetric asymmetric. At 600 nm really high material gain is necessary (628 cm^{-1}) to compensate propagation losses. Reference 4 demonstrates a net gain in the SPP propagation, but using thinner gold layers (4 nm). At 1500 nm the required gain reduces notably up to values around 12 cm^{-1}. In order to reach these gain values the QDs should exhibit a high Stokes shift between the absorption edge and emission (defining the wavelength of operation), in order to minimize reabsorption losses. The use of core-shell **PbS-CdS PER** Quantum Rods (QR) from UGENT is initially proposed as gain material (see MS17 for details on synthesis and experimental gain results in dielectric waveguides). The emission band of these QR is broad with the absorption edge at 450 nm, and preliminary experimental results of such nanocomposite in dielectric waveguides show gains of about 300 cm^{-1}.

λ (nm)	**complete loss compensation**	**10 dB/cm**
600	g=1571 cm^{-1} gain top g=628 cm^{-1} gain top and bottom	g=1613 cm^{-1} gain top g=775 cm^{-1} gain top and bottom
1550	g=20.3 cm^{-1} gain top and bottom g=12.1 cm^{-1} gain top and bottom	g=40.6 cm^{-1} gain top and bottom g=20.3 cm^{-1} gain top and bottom

Table I

CONCLUSIONS: optimized structures at 1550 nm

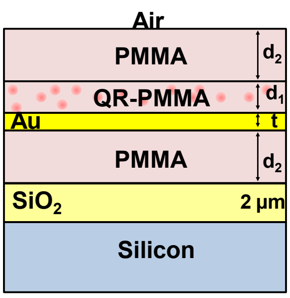

Figure 6. Optimal waveguide design.

In the last section it has been discussed that at 1550 nm there is a strong correlation between optical losses and single mode operation, given that cladding layer has to be thicker than 9 µm to keep the whole evanescent field, but high order TM modes appear. This problem can be overcome by usign a design like the one shown in figure 6. In this structure a thin layer of QD-PMMA is deposited at the top (or top and bottom) of the gold film and thick layers of PMMA surrounding the structure. In this way, if the thickness of the QD-PMMA is thin enough, the overlap of the active material with high order modes can be neglected and emitted light will be mainly contribute to compensate losses along the LR-SPP propagation [4]. An optimum value for this thickness is close to the FWHM of the transverse field, i.e., about ***d1 = 1.4 µm*** at 1550 nm (see figure 4b). Besides, given that high order TM modes are centred in the bare PMMA, if the cladding is thick enough the mode centre will be well separated from the QD-PMMA active layer. So, in principle the cladding has to be as thick as possible and ***d***$_2$***=10 µm*** has been initially chosen. Using this design the minimum gain to compensate for losses and obtain a net gain 10 dB/cm (considering gain only in the top layer) are now 63 and 125 and cm^{-1}, respectively, only a bit higher than the ones found in the last section and also achievable with the proposed QRs.

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Annex 1. Refractive indexes

Material	600 nm	1550 nm
Air	1	1
SiO_2	1.4582	1.4522
PMMA	1.489	1.483
Au	0.2203-3i	0.439-9.519i

Table I. Material's refractive indexes