Partial loss compensation in dielectric-loaded plasmonic waveguides at near infra-red wavelengths

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Abstract: We report on the fabrication and characterization of straight dielectric-loaded surface plasmon polaritons waveguides doped with lead-sulfide quantum dots as a near infra-red gain medium. A loss compensation of ~33% (an optical gain of ~143 cm^{-1}) was observed in the guided mode. The mode propagation, coupling efficiency and stimulated emission were characterized using leakage radiation microscopy. The guided mode signature was separated using spatial filters in the Fourier plane of the microscope for quantitative measurements of stimulated emission.

OCIS codes: (240.6680) Surface plasmons; (250.4480) Optical amplifiers; (250.5403) Plasmonics; (230.3120) Integrated optics devices.

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1. Introduction

Plasmonics has become an attractive research area since it has the potential to combine the fast response time of photonics and the sub-wavelength confinement of surface plasmon polaritons (SPPs) [1, 2]. Several of these studies focus on the development and characterization of passive plasmonic devices such as waveguides [3, 4], wavelength-selective filters [5], interferometers [6] and refractive elements [7], among others [8, 9]. In this context, dielectric-loaded SPP waveguides (DLSPPWs) have drawn special attention in the last years due to their ability to provide subwavelength transversal confinement to SPPs. Such a confined mode is called dielectric-loaded SPP (DLSPP) [10–12]. DLSPPWs are strips of a dielectric material (typically poly-methyl-methacrylate - PMMA) deposited on a metallic thin-film [13]. Unfortunately, increasing the confinement factor (CF) automatically results in a diminution of the mode propagation length. In order to overcome the trade-off between sub-wavelength confinement and propagation loss, gain media have been proposed to compensate ohmic loss through optical amplification [14]. In this context, optical amplification achieved with dye molecules [15–18], erbium ions [19] and quantum dots (QDs) [20–22] have been reported [23] at visible, near infra-red and telecom wavelengths with loss compensations of ~30%. We have reported earlier an optical gain of ~200 cm^{-1} and the corresponding propagation loss compensation of ~30% for SPP at near-infrared wavelength using lead-sulfide (PbS) QDs [24]. In this paper, we report on fabrication and characterization of straight DLSPPWs doped with PbS QDs for DLSPP mode amplification at near infra-red wavelengths. The optical gain was quantitatively measured by detecting the stimulated emission signal impinging directly on a photodetector. The waveguides were pumped with a Nd:YAG laser at 532 nm, whereas the DLSPP mode was excited with a continuous wave Ti:Sapphire tunable laser at the wavelength of 860 nm. A loss compensation of ~33% (an optical gain of ~143 cm^{-1}) was observed in the DLSPP mode. The mode propagation, coupling efficiency and stimulated emission were characterized by leakage radiation microscopy (LRM). The stimulated emission signal, which was originated only from the guided mode inside the waveguide, was separated and measured independently by inserting spatial filters in the Fourier plane of the microscope.

2. Active medium for DLSPPWs

The active medium was prepared by mixing the PMMA with PbS QDs (Evident Technologies). The concentration of the QDs in PMMA was chosen to be 2.8×10^{17} cm^{-3}. The mixture was deposited by spin coating over a 70 nm thick gold film that was previously deposited by thermal evaporation on a thin (0.17 mm) glass substrate. The thickness of the

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PMMA/PbS-QDs film was set to 300 nm which assures single mode operation of the DLSPPW [10]. To allow toluene to evaporate, the polymer film was baked for 2 minutes at 180 °C. The fabricated structures consist of a straight waveguide having a tapered coupler at one of its ends (Fig. 1(a)). The structures were imprinted using e-beam lithography and immersed in a MIBK/IPA(1:3) solution for resist development. It was observed that for higher concentrations of PbS QDs in the PMMA, the resulting waveguides showed defects, such as cracks and undesired roughness, which affect the DLSPP mode propagation. The chosen concentration allowed the fabrication of the structures with the desired properties, i.e. correct form and size as well as enough QDs in the PMMA in order to attain stimulated emission.

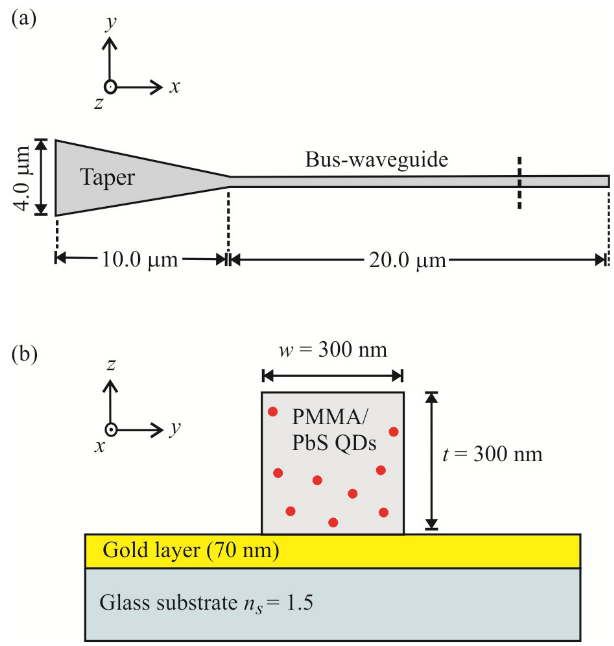

Fig. 1. (a) Straight DLSPPW. (b) Cross section along the dashed line in (a). The PbS quantum dots are embedded inside de PMMA film.

3. Experimental setup

The experimental setup consists of a LRM arrangement composed of a 20x (NA = 0.40) focusing objective (O1) and an oil-immersion objective (O2) with high numerical aperture NA = 1.45 that was used for collecting the leakage radiation of the DLSPP mode (Fig. 2(a)). A Nd:YAG laser (532 nm) was used as a pump laser and a tunable Ti:Sapphire laser set at 860 nm acted as a probe laser which coupled light into a DLSPP mode inside the waveguide. The pump laser beam was expanded to cover completely the straight section of the waveguide (Fig. 2(b)). The DLSPP mode is detected by collecting the corresponding leakage radiation appearing at the glass-substrate side of the sample [13]. Notice that the intensity of the leakage radiation is proportional to the intensity of the DLSPP mode, making it possible to evaluate the amplification of the mode.

Both laser beams were modulated by a double-frequency chopper (2FC) at the frequencies f_1 = 200 Hz and f_2 = 280 Hz connected to a lock-in amplifier (LIA). The difference frequency Δf = 80 Hz was used to detect the stimulated emission signal acquired from the structure. The incoming light from the pump laser was completely filtered out, after it has interacted with the sample (S), using band-pass filters (BPF), and neutral density filters (NDF) were used to attenuate the probe laser intensity in order to avoid saturation in the photodetector (PD).

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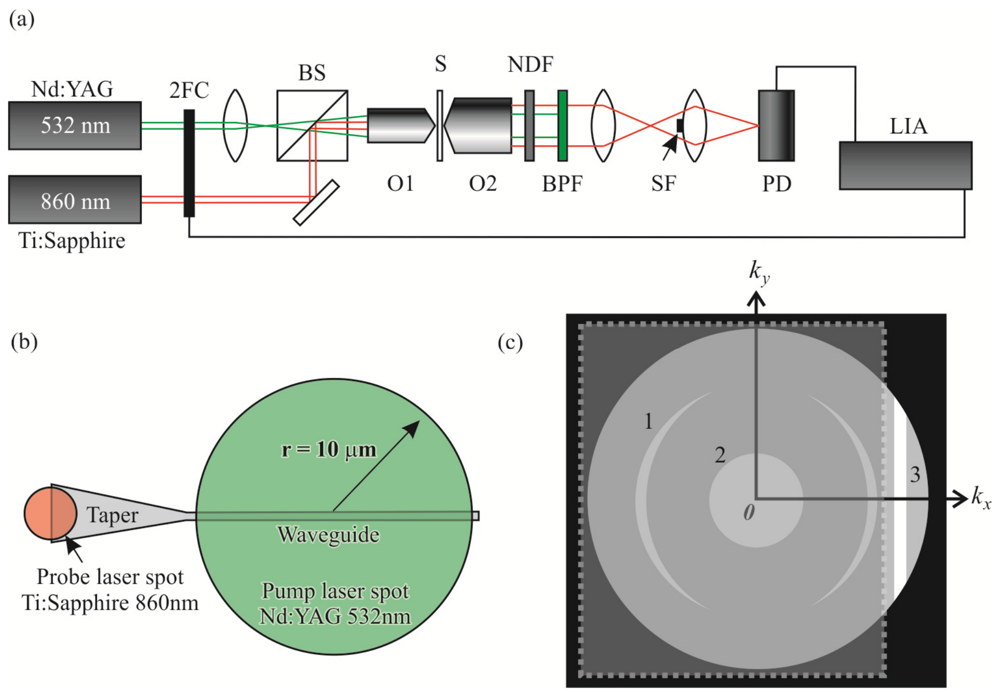

Fig. 2. (a) Experimental setup. A beam-splitter (BS) is used to combine both laser beams. (b) Active DLSPPW. The small circle in the left represents the size and position where the probe laser spot was focused to couple into a DLSPP mode inside the waveguide and the big circle corresponds to the pump laser. (c) Schematic of the Fourier plane showing the three main contributions: the gold-air SPP (1), the incident beam (2) and a straight line that corresponds to the guided mode signature (3). The shaded rectangle represents the spatial filter used in the experimental setup and only (3) reached the detector.

A spatial filter (SF) was placed in the Fourier plane of the microscope to eliminate all spatial frequencies which are different from the *k*-vector of the guided DLSPP mode. The guided mode is represented by a straight line in the Fourier plane and can be easily filtered out (Fig. 2(c)). Another lens was used for focusing the transmitted through the filter light onto the photodetector. This experimental setup allowed the measurement of either spontaneous or stimulated emission inside the DLSPPW by supplying the appropriate reference frequency to the LIA (f_1 or Δf, respectively).

4. Results and discussion

The propagation length of the DLSPP mode was numerically calculated (using finite element method) giving a value of 11.4 μm. This value corresponds to a DLSPP mode loss of ~438 cm^{-1}. The LRM image showed good confinement and effective guiding of the mode through the DLSPPW (Fig. 3(a)). The oscillations of the intensity along the profile are common in LRM technique and arise from interference of the main LRM signal with close spatial components, such as those leaking from a mode in the taper region, which has different effective index (Fig. 3(b)).

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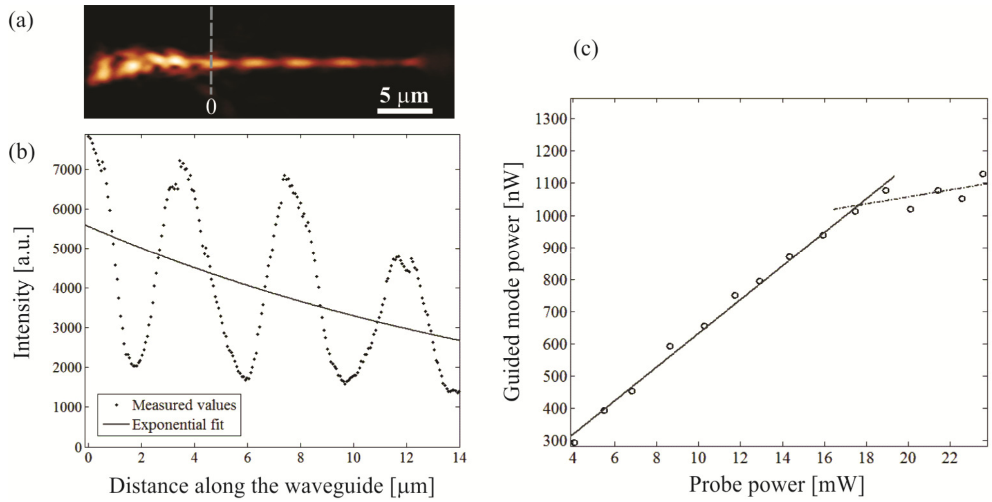

Fig. 3. (a) LRM image of the DLSPP mode propagating along the waveguide. (b) Intensity profile of the guided mode along the waveguide. (c) Guided mode power plotted for different values of the probe laser power in the absence of the pump laser.

We next measure the coupling efficiency and the stimulated emission signal. For this purpose, the probe laser beam is coupled into the DLSPPW by focusing the Gaussian beam to a spot size of 5μm on the edge of the taper side of the waveguide, (Fig. 2(b)).Three main contributions can be observed in the Fourier plane of the microscope (Fig. 2(c)): the one from the gold/air SPP, the directly transmitted light and the corresponding contribution from the DLSPP mode. A spatial filter is placed in such a way that only the signature corresponding to the guided mode reaches the photodetector (Fig. 2(c)). The power corresponding to the DLSPP mode is measured for different values of probe power in the absence of the pump (Fig. 3(c)). This dependence must be linear and thus the coupling efficiency can be estimated directly from the slope of the curve [24]. The efficiency evaluation indicates very weak coupling into the waveguide (~0.006%) probably due to imperfections in the structure. The dependence of the guided mode power on the probe power exhibits a change in the slope when the probe power exceeds 17 mW. The slope decreases indicating even lower coupling efficiency that can be explained by a physical damage of the PMMA film that constitutes the taper. This result indicates a reliable range of the probe power (≤ 16 mW) for measurements of stimulated emission. The PMMA with embedded PbS QDs can act as an active medium if the stimulated emission couples into a DLSPP mode in the waveguide [17]. In such a case, optical amplification can be achieved resulting in an increment of the propagation length. An effective and non-destructive irradiance interval for the pump laser was found (between 1000 and 4500 W/cm^2). Stimulated emission measurements below this interval are almost in the noise level (~50 nW) and higher powers start to melt the PMMA film. An optical gain of ~143 cm^{-1} was measured for a probe power of 16 mW and pump irradiance of ~4460 W/cm^2, which corresponds to a compensation of ~33% of the DLSPP mode loss (Fig. 4(a)). The linear dependence of stimulated emission, when measured against pump power, indicates that population inversion is completely achieved for a pump irradiance higher than 1000 W/cm^2 (Fig. 4(b)).

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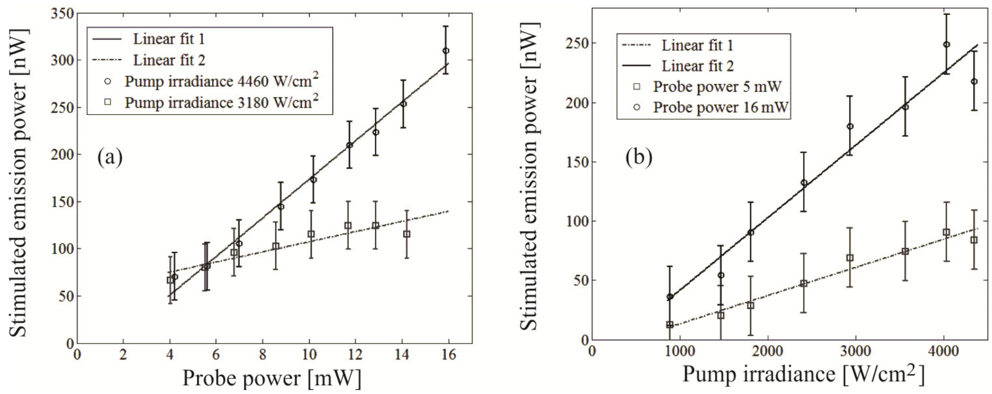

Fig. 4. (a) Stimulated emission measured for different powers of the probe laser. Two values of the pump irradiance are also shown. (b) Stimulated emission dependence measured for different values of the pump irradiance at fixed probe power. Two different values of probe laser powers are plotted.

Here, one should take into account that QDs suffer from photobleaching which is accelerated when pumping the QDs. The photoluminescence of the QDs decreased continuously during the course of the experiments, therefore, affecting the reproducibility of the experiments. When the stimulated emission power was measured for two different values of the pump irradiance (Fig. 4(a)), the first set of measurements led to slight QDs photobleaching (at pump irradiance of 3180 W/cm^2) which resulted in lower initial values of the stimulated emission in the second set of measurements (at pump irradiance of 4460 W/cm^2) and in an apparent intersection of the linear fit. Nevertheless, it is clear that higher values of stimulated emission were achieved for higher powers of the probe laser.

5. Conclusions

We have demonstrated the feasibility of separating and measuring quantitatively the stimulated emission signal that was originated only from the DLSPP mode that propagates along the waveguide. This alternative constitutes an important improvement in the detection of stimulated emission signals along DLSPPWs. The optical amplification of DLSPP guided mode was achieved at near infra-red wavelengths. An optical gain of ~143 cm^{-1}, which corresponds to ~33% of loss compensation, was evaluated from the experiments. The inherent photobleaching and low stability of the QDs hinder reproducibility, and thus complicates the statistical treatment of experimental data. However, in this work, optical amplification and relative stability of the QDs was observed for low pump irradiances. Based on the results obtained here, as well as in previous works [15–24], we conclude that it is in general rather difficult to obtain loss compensation above ~30% due to the thermal damage of the structures and active medium photobleaching. Hence, a search of new, more promising, active media for amplification of plasmonic modes remains to be an open problem.

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