Confining light in optical fibres using surface plasmon polaritons

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Efficient light confinement in optical fibres is demonstrated using surface plasmon polaritons.

1. Introduction

In modern photonics sources with extremely small spotsize are highly desirable. Recent results show that "sub-wavelength" light sources can be manufactured using many techniques and have a wealth of applications, including optical memories, optical tweezers, SNOM microscopy and photolitography, just to cite a few.

Light confinement is limited by diffraction, which can be seen as a direct consequence of Heisenberg's uncertainty principle:

$$\Delta x \cdot \Delta p_x \geq \frac{\hbar}{2} \tag{1}$$

where Δx is the minimum spatial detail and represents the confinement limit, and Δp_x is the uncertainty of the photon momentum in the x direction. Using simple calculations the maximum confinement can be expressed as a function of the wavelength λ_0 and the refractive index of the medium where light propagates:

$$\Delta x \geq \frac{\lambda_0}{2n} \tag{2}$$

Eq. (2) represents the diffraction limit. However, the possibility to overcome the diffraction limit is already included in Heisenberg's principle: in fact, eq. (2) was derived assuming that

$$k_x \leq k \tag{3}$$

Since k_x is defined as:

$$k_x = \sqrt{k^2 - k_z^2 - k_y^2} \tag{4}$$

for imaginary k_z or k_y (evanescent fields) k_x is no more limited by the value of k [1].

All the proposed experiments trying to overcome the diffraction limit are based on the evanescent field assumption. Metamaterials proposed by Veselago [2] have both negative dielectric constant and magnetic permeability, thus a negative refractive index n. Engineered nanostructured materials fabricated by Pendry had a negative refractive index and worked as superlenses [3].

Sub-wavelength light confinement can be achieved in a classical way exploiting the field enhancement that can be obtained at the interface between materials with a high refractive index difference [4]. This method is based on the continuity of the normal components of the displacement vector at the interface; as a consequence, confinement improves only in one direction and it is strongly limited by the refractive index difference between the waveguide and the surrounding medium [4].

In this manuscript, light confinement is achieved in optical fibres using surface plasmon polaritons (SPP).

2. Surface plasmon polaritons

SPP can be described as an oscillation of metal free electrons. This oscillation can be induced when radiation with a transverse magnetic (TM) polarisation hits the interface between dielectric and metallic media at a specific angle.

The metal has to be chosen in order to have small losses, i.e. a small imaginary part of the dielectric constant. In this work gold is used. The resonance condition to excite SPP consists in matching the projection of the propagation constant of light to the propagation constant of SPP (β) along the direction of propagation of the SPP:

$$k \sin\alpha = \beta \tag{6}$$

Focusing using SPP has already been demonstrated in free space with nanostructures like gratings [5, 6], but the overall conversion efficiency is extremely poor. The use of optical fibres allows for an extreme control on the light propagation properties and an efficient conversion into SPP.

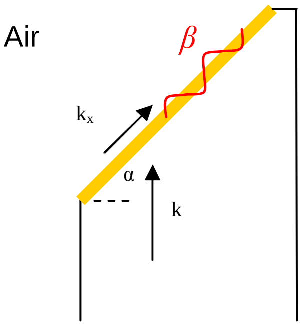


Fig.1 – Schematic of the proposed design

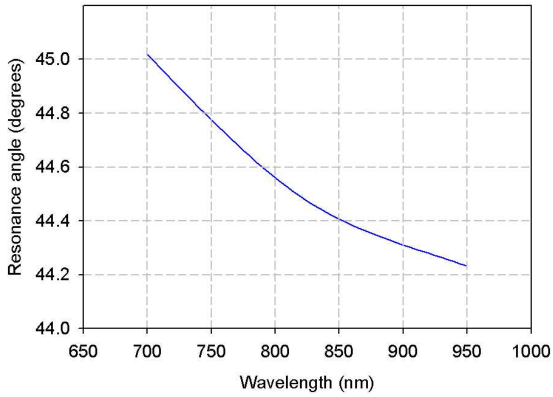


Fig. 2 – Resonance angle with wavelength

A schematic of the device is proposed in Fig. 1. The proposed design allows for a very small spotsize, high brightness and all the benefits related to fiberised sources.

The resonance condition (6) for the SPP propagating at the interface between gold and air can be written as a function of the dielectric constants of air (ε_{air}) and gold (ε_{met})[7]:

$$\frac{\omega}{c} n_{eff} \sin\alpha = \frac{\omega}{c}\left(\frac{\varepsilon_{met}\varepsilon_{air}}{\varepsilon_{met}+\varepsilon_{air}}\right)^{\frac{1}{2}} \tag{7}$$

(n_{eff} is the effective index of the fundamental mode HE_{11}).

Eq. (7) allows to evaluate the dependence of the resonance angle on the wavelength: results are summarised in Fig.2. It is clear that a marginal change in the value of the resonance angle occurs in the wavelength range 700-950nm, therefore manufacturing tolerances on the angle cleaving are reduced to a mere ±0.3°.

3. Experimental results

The sample used in these experiments was manufactured from an optical fibre singlemoded at 800nm. Numerical aperture (NA), cut-off wavelength (λ_c) and core diameter were, respectively, 0.13, 730nm and 4.296µm. The fibre was cleaved with a CO_2 laser and then coated with 40nm of gold. The final cleaving was performed with the aid of a Focused Ion Beam system (FEI Inc.) to uncover a portion of the core. The manufactured sample is shown in Fig. 3.

To probe the contribution of SPP to the overall transmissivity, the sample was connected to the optical set-up shown in Fig.4.

Fig. 3 – SEM picture of the sample

A supercontinuum source, delivering 400fs pulses with a max pulse energy of 50nJ over the wavelength range of 450-1800nm, was used to launch light into the sample. The source fiberized pigtail was fixed onto an XYZ stage to optimise the coupling into a modal filter [8] used to remove the higher order modes. The modal filter was spliced to the sample fiberised pigtail to minimise the loss and avoid the introduction of additional Fabry-Perot cavities. The sample was then fixed onto another XYZ stage and positioned in front of a multimode fibre, which was used to collect the transmitted light into an OSA.

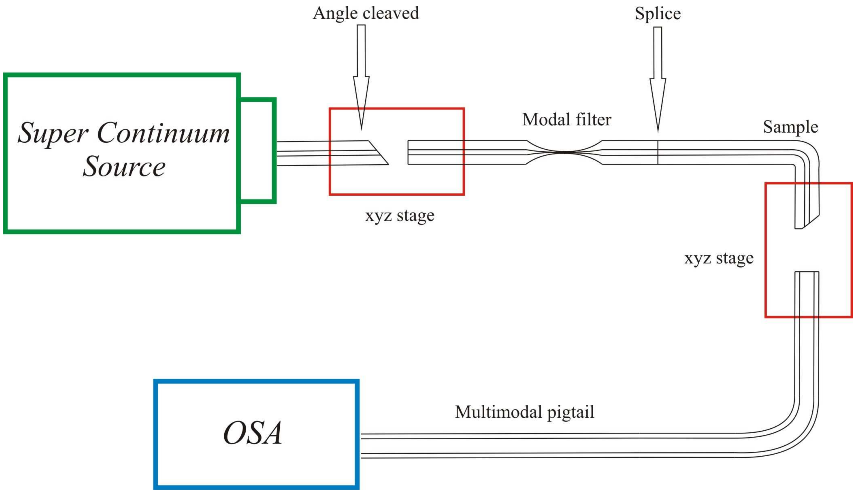
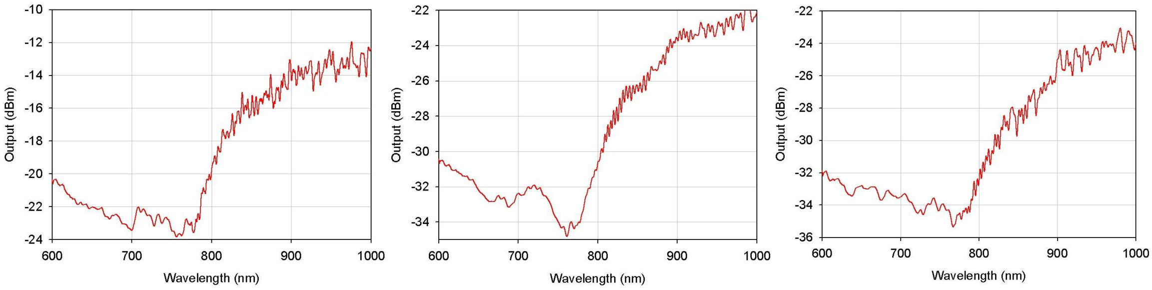


Fig.4 – Optical set-up

Spectra recorded by the OSA are reported in figure 5. Fig.5a shows the measurement carried out without the sample and the modal filter, which was used as a reference for following measurements.



a b c

Fig. 5 – Results of the measure:a) without sample, b) with sample, c) with sample in humid environment

Fig.5b and Fig 5c show the measurements performed on the sample in dry and humid air (obtained gently breathing over the sample).

A comparison between Figs. 5a and 5b clearly shows the presence of a peak in the wavelength range 700-750nm in Fig. 5b. The peak disappears in Fig. 5c because of the change of the SPP resonance conditions, due to the change in optical properties related to the humidity level change. When the humidity level decreases to the environmental value, the peak reappears and the transmission spectrum looks again like the one in Fig. 5b. This behaviour is

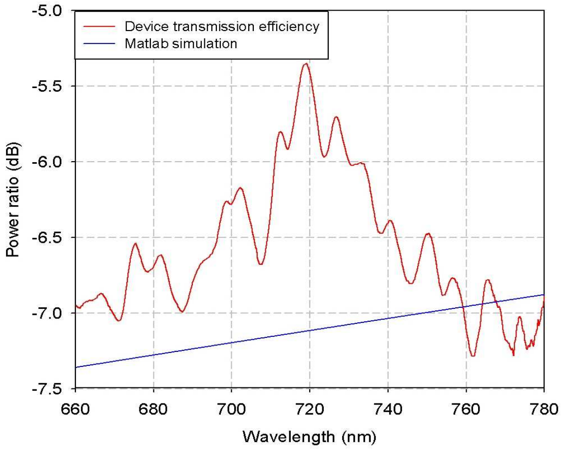


Fig. 6 - Transmission of the sample

compatible with the presence of a surface plasmonic resonance peaked at 720nm.

Fig. 6 shows in red the ratio between the traces reported in figs. 5a and 5b. The transmission through the uncoated aperture due to geometrical considerations is reported in the same figure in blue. The power transmitted through the aperture (without the contribution of SPP) has been calculated assuming the sample end as shown in Fig. 7. No transmission was considered for the section coated with gold. The growing slope observed in the blue line of fig. 6 can be ascribed to the decreasing level of confinement experienced by the mode at longer wavelengths. The two end-face reflections and the modal filter attenuation observed in the measurement of Fig. 5b are not considered in the simulations.

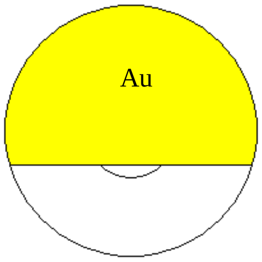


Fig. 7 – Schematical description of the sample

Several small ripples have been observed over the whole range of wavelengths in all measurements and have been attributed to the presence in the line of Fabry-Pérot interferometers due fibre end facets (in the modal filter, at the multimode fibre) and to the splicing point.

Fig. 6 clearly shows that the presence of SPP enhanced the transmission by ~1.7dB, increasing the overall transmission from 20% (at the spectrum extremities) to 30% (at the peak centre).

4. Conclusions

This experiment demonstrates that it is possible to have enhanced confinement in an optical fibre using surface plasmon polaritons. Theoretical considerations on the plasmon dispersion curve predict that confinement to 5nm can be possible. The use of optical fibres allows to efficiently convert propagating light into surface plasmon polaritons, thus the same geometry proposed in fig. 1 should allow for an extremely bright light source which overcomes the diffraction limit. Efficiency improvements can be achieved using different geometries: if the fibre end is cut with a V shape instead of a single cut, the propagation path of the plasmon and its attenuation are considerably decreased. Moreover, the use of light from a source with TM polarization can increase considerably the conversion efficiency of light in surface plasmon polaritons.

References

[1] D. Courjon and C. Bainier, "Near field microscopy and near field optics", Rep. Prog. Phys., Vol.57, 1994, pp.989-1028

[2] V. Veselago, "Electrodynamics of substances with simultaneously negative electrical and magnetical permeabilities", Sov. Phys. Usp., Vol.10, 1968, pp.509-514

[3] J.B. Pendry, "Negative Refraction Makes a Perfect Lens", Physical Review Letters, Vol.85, N.18, 2000

[4] G.S. Wiederhecker, C.M.B. Cordeiro, et al., "Field enhancement within an optical fibre with a subwavelength air core", Nature Photonics, Vol.1, 2007, pp.115-118

[5] H.F. Ghaemi, T. Thio, et al., "Surface plasmons enhance optical transmission through subwavelength holes", Physical review B, Vol.58, N.11, 1998

[6] L. Salomon, F. Grillot, et al., "Near-Field Distribution of Optical Transmission of Periodic Subwavelength Holes in a Metal Film", Physical Review Letters, Vol.86, N.6, 2001

[7] S. Maier, "Plasmonics. Fundamentals and Applications.", ed. Springer. New York, 2007

[8] Y. Jung, G. Brambilla and D.J. Richardson, "Broadband single-mode operation of standard optical fibers by using a sub-wavelength optical wire filter", Optics Express, Vol.16, N.19, 2008, pp.14661-14667