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Light propagation in metal-coated SNOM tips: experiment and numerical simulations

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Introduction

•The **mesoscopic** effect **of spectral modulation (MSM)** can be observed for a broadband light transmitted by a multimode fiber terminated with a SNON tip due to the interference of at least two remaining photonic modes at the exit [1]. Our experimental setup shown in Fig. 1.

•Observation of spectral modulation indicates the occurrence of finite differences of **optical path differences (OPD)** for a small number of output modes. We use the mode-filtering effect of a SNOM tip to virtually eliminate all but two fiber modes. In the two-mode case, a sinusoidal spectral modulation with frequency equal to OPD is expected at the exit (Fig. 2).

•Using the MSM-based two-mode experimental technique [1], the **modal dispersion** has been studied for several SNOM tips coated with Cr and Al metal layers of thickness 20 and 200 nm respectively [2,3]. This modal dispersion turned out to be of much higher magnitude and of the opposite sign compared to the inherent modal dispersion of the fiber tail.

•These results were attributed to a mode-selective coupling of photons to surface plasmons of the metal coating. However, comparison of new results obtained for Cr/Al and Cr/Au coatings does not show any dramatic differences in the modal dispersion of SNOM tips (Fig. 3).

•To get an insight on the propagation of electromagnetic excitations in our SNOM tips, we initiated numerical simulations based on the theory outlined in Ref. [4]. Presented are some initial results (for a model shown in Fig. 4) of ongoing Comsol simulation efforts. (Figs. 5,6)

Experimental setup

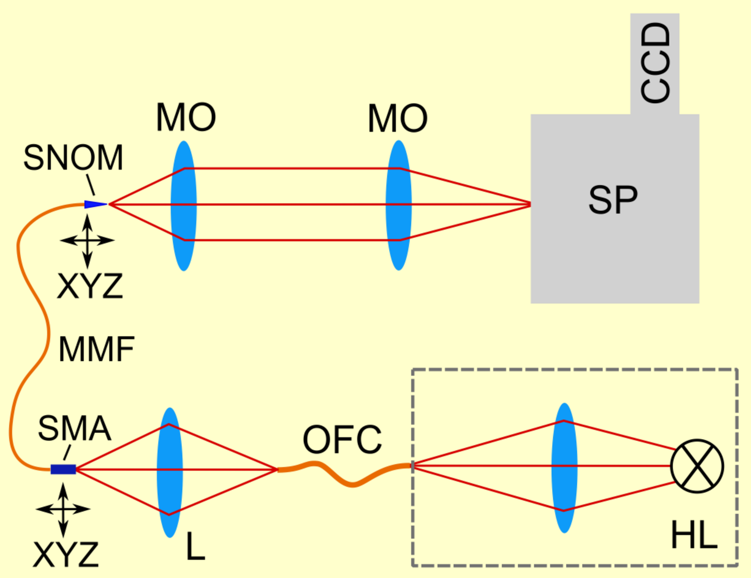

Fig. 1. Optical scheme of the experimental setup.

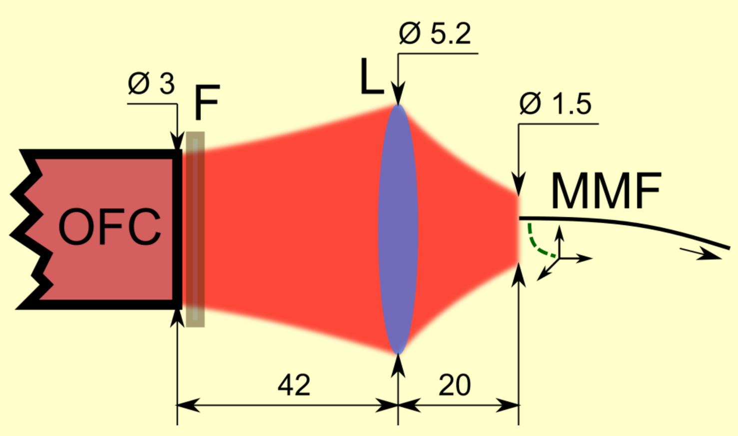

Fig. 1a. Schematic explanation of the multimode optical fiber (MMF) excitation by the broadband light from optical fiber cable (OFC).

- HL – 150 W halogen lamp coupled in a high-intensity illuminator MI-150 (Dolen-Jenner) to a 3 mm output diameter optical fiber cable (OFC).
- L – focusing lens, f=13.86 mm.
- MMF – multimode optical fiber of length *l*, terminated at the input by an SMA connector and at the rear end - by a SNOM tip; positions of both terminals can be adjusted by XYZ micrometric translation stages.
- SP – spectrometer Shamrock SR-303i coupled to CCD camera Newton (Andor).
- MO – microscope objectives used to couple the SNOM output light into SP.
- F – an optional red-pass filter.
- The radiation from the OFC output face is focused by L to a ~1.5 mm diameter "spot" in the transverse (image) plane, which contains the input face of MMF (the cladding outer diameter is 125 μm) with laterally adjustable position within this plane; the spectrum measured by SP appears to depend on this adjustment.
- All dimensions are in millimeters.

References

[1] M. Rähn, M. Pärs, V. Palm, R. Jaaniso, V. Hizhnyakov, Opt. Commun. 283 (2010) 2457.
[2] V. Palm, M. Rähn, V. Hizhnyakov, Opt. Commun. 285 (2012) 4579.
[3] V. Palm, M. Rähn, J. Jäme, V. Hizhnyakov, Proc. SPIE 8457 (2012) 84572S.
[4] L. Novotny, C. Hafner, Phys. Rev. E 50 (1994) 4094.

Fiber tail length dependences of OPD

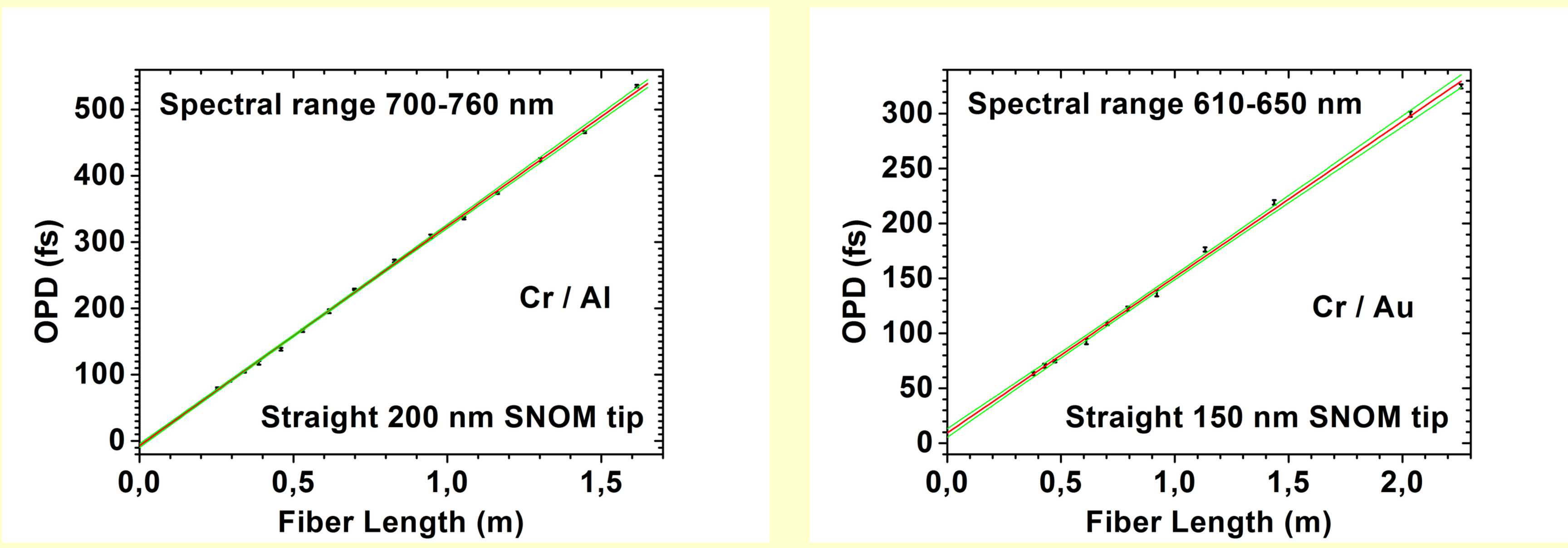

Fig. 3. OPD values τ calculated according to the two-mode model for different fiber tail lengths *l*. Red line – a linear fit according to the expression: $\tau(l) = A + Dl$, where $A = \tau(0)$ denotes the OPD value generated in a SNOM tip, *D* – the MM fiber intermodal dispersion parameter. Green lined mark the 95% confidence interval.

Cr/Al SNOM tip ($\lambda \approx 730$ nm): $A = -7.0 \pm 1.3$ fs; $D = 331.0 \pm 2.2$ fs/m.

Cr/Au SNOM tip ($\lambda \approx 630$ nm): $A = 9.4 \pm 1.8$ fs; $D = 141.8 \pm 1.7$ fs/m (the signs can be flipped).

Examples of transmitted light spectra

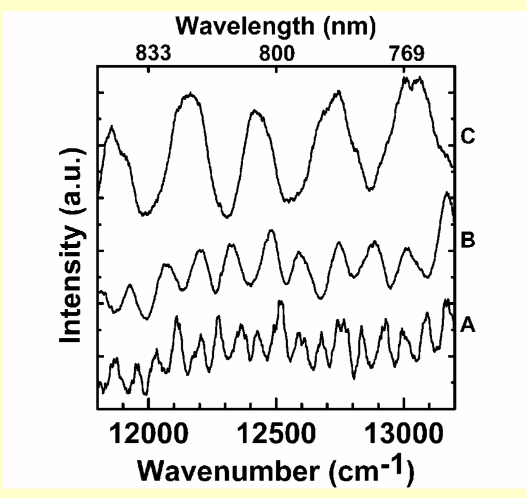

Fig. 2. **MSM effect** observed for a 200 nm SNOM tip (Cr/Al coating) with three different fiber tail lengths *l*. Baselines are shifted for clarity.
A: *l* = 769 mm
B: *l* = 479 mm
C: *l* = 240 mm

By fitting the spectral positions of several sequential maxima with a linear regression, an average OPD value can be easily estimated for a certain spectral interval.

A model structure

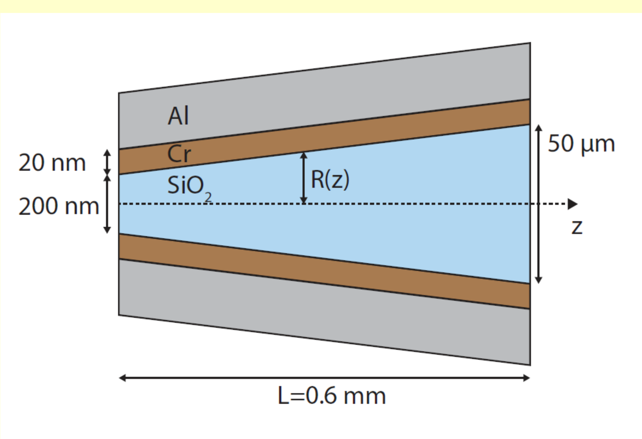

Fig. 4. A model structure representing a SNOM tip, as used for the first Comsol simulations.

Parameters of 10 strongest modes

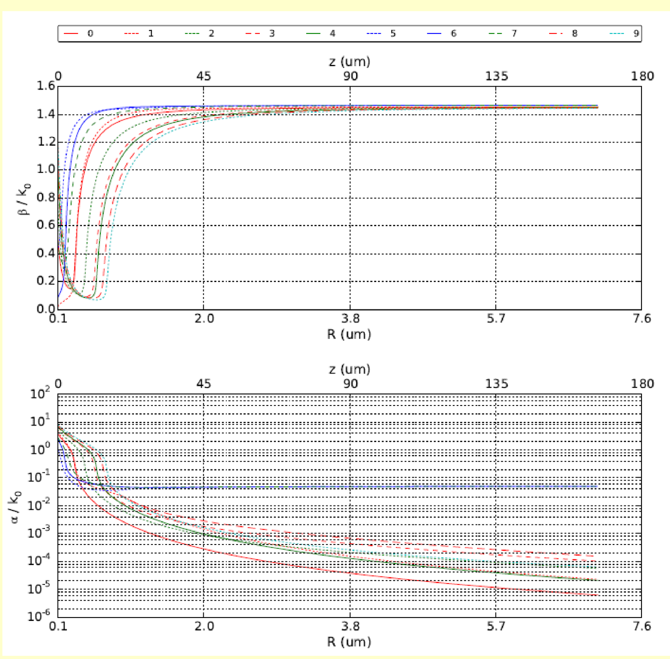

Fig. 5. Coordinate (z) and radius (R) dependence of complex refractive index real- and immaginary parts for 10 strongest modes propagating in the structure.

Conclusions

The observed two-mode optical path difference (OPD) consists of two contributions: the OPD in the non-coated MM fiber due to its inherent modal dispersion (characterized by parameter *D*) and the OPD generated in a metal-coated SNOM tip (described by parameter *A*), which is influenced by a mode-selective photon-plasmon coupling.

Difference of *D* values for the two fibers from Fig.3 can be explained by different spectral regions used. Assuming opposite signs of these *D* values, the parameter *A* values obtained for SNOM tips with Cr/Al and Cr/Au coatings are virtually identical.

According to our tentative conclusion, a thin (20 nm) Cr layer appears to play the main role for different modes of surface plasmon polariton waves generated on its interface with SiO_2 fiber. Our initial simulations indicate that typically only a subtle part of the electromagnetic energy reaches the outer metal layer (see samples in Fig. 6), which explains its small influence on the modal dispersion observed for SNOM tips.

EM field structure calculated for two sample modes

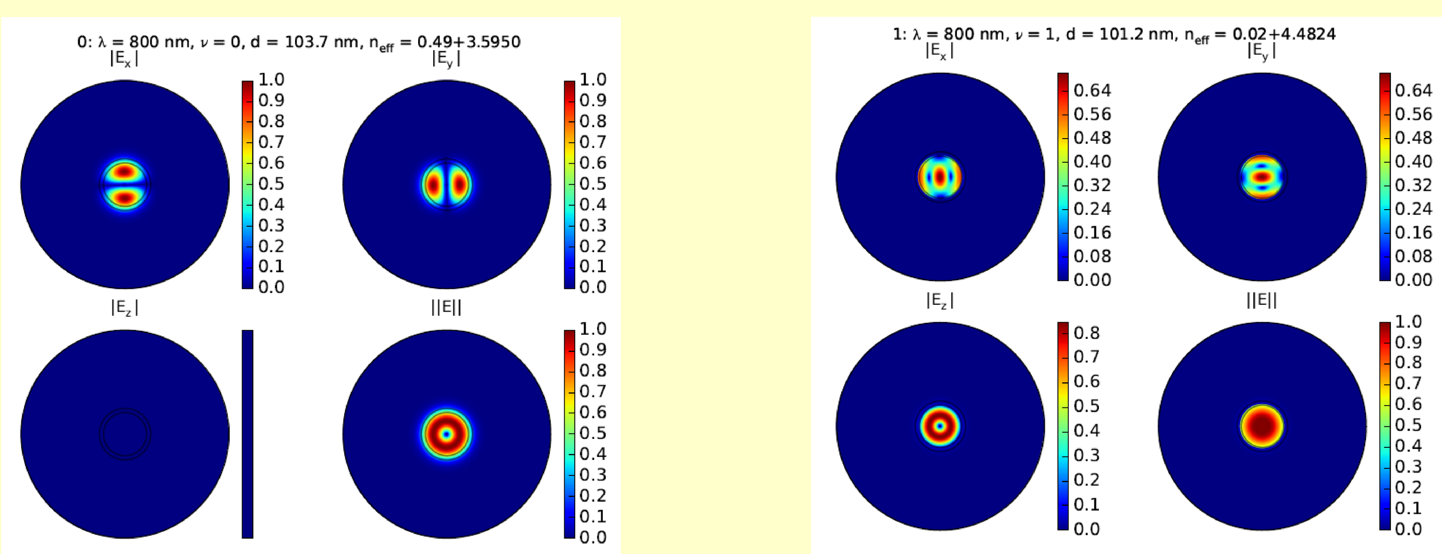

Fig. 6. Structure of electromagnetic field at R ≈100 nm position for two sample modes.

Acknowledgements

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