

Plasmonic effects in metal filled microstructured optical fibers

R. Spittel, D. Hoh, K. Schuster, J. Kobelke, H. Bartelt
 Institute of Photonic Technology, Albert-Einstein-Str. 9, 07745 Jena, Germany
 mailto:ron.spittel@ipht-jena.de

By blocking selected holes of photonic crystal fibers and filling them with liquid gold, we are able to introduce micron sized wires into silica fibers. We show that it is possible to excite surface plasmon polaritons by coupling from a fiber core mode and we will compare the experimental and the theoretical results using semi-analytical calculations and a finite element method.

1 Introduction

We have applied a technique to fill selected holes of microstructured optical fibers (MOFs) with metals. We do this by blocking the holes with an UV-curing adhesive using a microscope and a 3-axis translation stage. The MOF is then placed into a silica capillary inside a tube furnace which is heated up to 1150 °C.

By using pressurized argon, we pump the metal into the MOF cavities at pressures of almost 200 bar. The smallest holes we were able to fill with this procedure have a diameter of 400 nm, which is close to the theoretical limit of our setup. The resulting micrometer sized wires permit excitation of surface plasmon polaritons (SPPs) and could also be used as electrodes for electro-optical effects in MOFs. We focus on the study of the surface plasmon polariton properties of the wires. Figure 1 shows a scanning electron microscope image of the fiber sample with a single gold wire which we will investigate in this work.

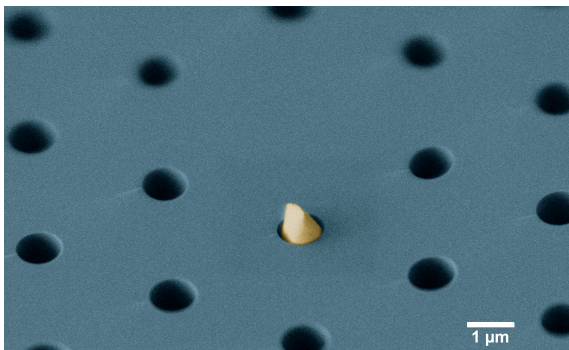


Fig. 1 Pseudocolor scanning electron microscope image of a MOF selectively filled with gold in a hole adjacent to its core.

2 Theory

Starting from Maxwell's equation [1] we can derive the dispersion equation of a cylinder described by the permittivity ε_1 embedded in an infinite cladding

medium with ε_2 and obtain

$$(\Psi_1 + \Psi_2) (\varepsilon_1 \Psi_1 + \varepsilon_2 \Psi_2) = m^2 n_{\text{eff}}^2 V^4, \quad (1)$$

with

$$\Psi_1 = W^2 \left(m - U \cdot \frac{J_{m+1}(U)}{J_m(U)} \right) \quad (2)$$

$$\Psi_2 = U^2 \left(m - W \cdot \frac{K_{m+1}(W)}{K_m(W)} \right). \quad (3)$$

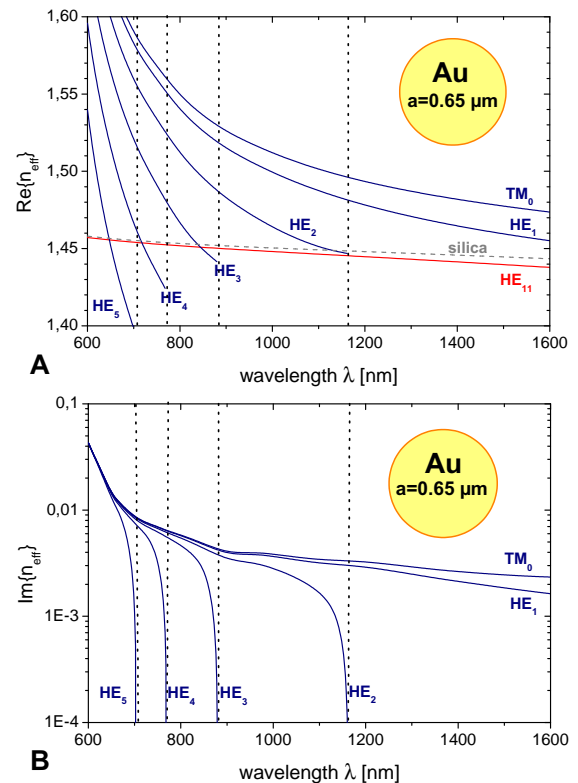


Fig. 2 Real (A) and imaginary (B) part of the effective mode indices of the fundamental core mode (red line) and the first 6 surface plasmon polaritons (blue lines) of a gold wire ($a = 0.69 \mu\text{m}$) in silica. The dashed line represents the refractive index of silica.

Here k_0 is the free space wave vector, a is the wire radius, $U^2 = k_0^2 a^2 (\varepsilon_1 - n_{\text{eff}}^2)$, $W^2 = k_0^2 a^2 (n_{\text{eff}}^2 - \varepsilon_2)$,

$V^2 = U^2 + W^2$, m is the azimuthal mode order and n_{eff} the effective mode index of the SPP. $J_m(x)$ and $K_m(x)$ are the Bessel functions of first kind and modified Bessel functions of first kind, respectively.

Figure 2A shows the effective mode indices of the first 6 surface plasmons ($m = 0 \dots 5$) with respect to the wavelength. Here we used literature values from Johnson & Christy[2] as source for the permittivity of gold. The refractive index of silica was taken from the Sellmeier equation[3]. The HE_{11} core mode of the unfilled MOF was calculated using a finite element method (FEM). One can see that the effective indices of all SPP modes with order $m \geq 2$ reach values below the silica line, which then disappear at a specific cutoff wavelength. This is due to the complex permittivity of gold. Around these cutoff wavelengths, the electromagnetic fields of the surface plasmons lose their bound character and extend to infinity which is associated with the vanishing losses according to figure 2B.

3 Transmission spectrum

To verify an interaction between the HE_{11} mode and the surface plasmons of the gold wire, we measured the transmission spectra of a 13 mm long selectively filled fiber sample. We used a commercial supercontinuum light source, which was coupled into a pre-fiber to obtain a gaussian beam shape with approximately the same mode field diameter as the fundamental mode of the fiber under test. This mode field was collimated and then focused on the core of the MOF. Since the fiber is extremely short and has no coating (due to the filling process), a high number of cladding modes are also guided which do not interact with the gold.

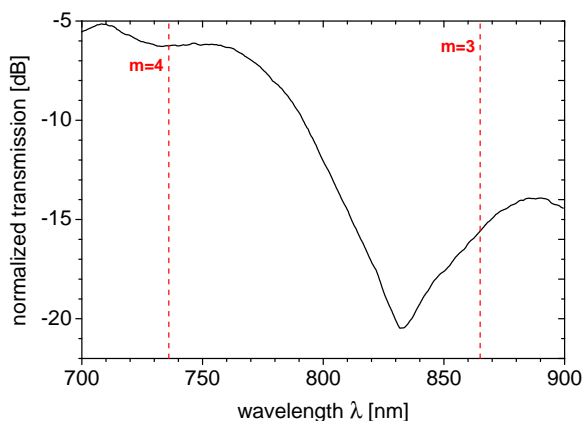


Fig. 3 Normalized transmission spectrum of a selectively filled PCF. The dashed lines represent the theoretical phase matching wavelengths for $m = 3$ and $m = 4$.

To solve this issue we placed an iris aperture in the collimated beam behind the MOF in order to spatially filter all light components but the core guided light. The transmitted light was coupled into an optical spectrum analyzer (OSA). To normalize the spectrum we also measured an unfilled fiber sample of the same length.

Figure 3 shows the normalized transmission spectrum of the fiber shown in figure 1. A dip of -10 dB is clearly visible around 833 nm, which is caused by energy transfer from the fundamental optical mode to a surface plasmon polariton. The dashed line ($m = 3$) represents the phase matching point between the HE_{11} and the HE_3 surface plasmon at 865 nm, as calculated in the preceding section. We consider that the observed blue shift of about 32 nm results from a small air gap between gold and silica, due to the strong contraction of gold during cooling after the filling process. Furthermore, the assumed simulation parameters may not perfectly match the real values of permittivity or of the wire radius. A smaller dip can be observed at 735 nm caused by coupling to the SPP of order $m = 4$ (HE_4).

4 Conclusions

We successfully verified mode coupling from the MOF core mode to the $m = 3$ and $m = 4$ surface plasmon polariton of a gold wire adjacent to the fiber core. The experimental results essentially correspond to the theoretical predictions of our semi-analytical and FEM calculations, but we noticed a blue-shift of the surface plasmon resonance between experiment and theory which may be explained by a small air gap around the gold wire or by a mismatch of the wire radius.

Acknowledgement

This work was supported by Federal State Thuringia in the framework of the European Fond for Regional Development (EFRE).

References

- [1] G. P. Agrawal, *Nonlinear Fiber Optics*, 3rd ed. (Academic Press, 2001).
- [2] P. B. Johnson and R. W. Christy, "Optical Constants of the Noble Metals," *Physical Review B* **6**, 4370–4379 (1972).
- [3] J. W. Fleming, "Dispersion in $\text{GeO}_2\text{-SiO}_2$ glasses," *Appl. Opt.* **23**, 4486–4493 (1984).