Microfluidic chemical deposition moves optical fiber to the nanoscale

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Optical fibers are fundamental to the information age and are now used not only for long-distance telecommunications but also for chemical sensing, fiber lasers, laser power delivery, and imaging, among many other applications. The fibers are drawn from silica or other types of glass or amorphous-polymer preforms. Because molten crystalline materials do not have viscosities compatible with fiber drawing, the useful material properties of optical fibers have been limited primarily to those of glass and polymer. If the material properties of crystalline semiconductors and metals could be integrated into optical fibers, many more fiber devices that generate, modulate, detect, or even guide or focus light at the nanoscale could become possible. We have developed a novel microfluidic chemical-deposition technique for fabrication of metal and semiconductor structures at dimensions down to the nanoscale within the pores of microstructured optical fibers (MOFs; see Fig. 1).

The use of a novel chemical-vapor-deposition process to integrate metals and semiconductor films in microstructured optical fibers may soon enable nanometer-scale waveguides and endoscopic cameras.

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optical fibers, overcomes mass-transport constraints and enables a strikingly uniform, dense, and conformal annular deposition onto the heated pore walls. It was found that the hole from which deposition occurs could close down to less than 10 nm in diameter, allowing for fabrication of essentially solid wire waveguides and demonstrating the high perfection of the deposition process (see www.laserfocusworld.com/articles/255490).

The process is strikingly simple, involving heating only very small quantities of a high-pressure precursor constrained within the interior of the MOFs (see Fig. 2).

FIGURE 2. In the fiber-filling process, a precursor fluid mixture is configured to flow into the pores of a MOF at high pressure (red arrow, left). When the entire MOF is heated, well-developed annular films are deposited in each pore (green layer). A single pore is shown for simplicity. (Courtesy of Penn State)

Microstructured optical fibers fabricated at the Southampton Optoelectronics Research Centre (ORC) can have dense arrays of capillaries with diameters down to nanoscale dimensions (10 to 100 nm) and lengths from meters to kilometers. The fibers can be engineered to have virtually any desired periodic or aperiodic spatial configuration. Silica MOFs are thus versatile nanotemplates that have extreme aspect ratio, are highly scalable, possess engineered geometries combined with unparalleled optical transparency, and tensile strength ten times greater than that of steel. Thus, wire materials can be deposited within the templates in virtually any desired two-dimensional (2-D) spatial configuration.

The added structural complexity of MOFs compared to conventional optical fibers means they exhibit completely new properties such as endlessly single-mode guidance, photonic bandgaps, and dispersion engineering for creating enhanced nonlinear effects such as supercontinuum generation. Microstructured optical fibers are a subset of a larger class of metamaterials that have been of great interest for novel applications ranging from negative-index materials to superlenses to chemical sensing. Incorporating precisely structured metals and semiconductor materials into MOFs thus greatly increases the possibilities for manipulating light within this platform.

Nanoscale guiding and imaging
Metal-filled fiber structures have already started to inspire a new body of research in “fiberized” plasmonic devices for applications in nonlinear optics and molecular sensing. Traditional plasmonic devices based on a 2-D geometry typically use a prism to phase-match the incoming ra-
diation with the surface plasmon wave, adding un-
wanted bulk and complexity. In the unique guiding
geometry of MOFs, the silica core acts as a prism
to couple transmitted light with plasmons at the air-
metal interface.

Based on this approach, researchers have conduc-
ted several theoretical studies of the transmission
properties of metal-dielectric MOF devices rang-
ing from fibers with thin coatings on the capillary
walls to solid nanowire inclusions. The results have
shown that careful choice of the metal thickness and
the design of the MOF can determine the wavelength,
the number of plasmon resonances, and the loss-
es within the device (see “Tuning of surface plasmons
leads to new optoelectronic devices,” p. 103).

A key advantage of our high-pressure chemical fluid-deposition
technique is the ability to organize potentially
thousands to millions of nanowires of metal, semiconductors, and dielectrics
in highly ordered arrays within the cross
section of a fiber. This enables a new class
of nanoscale imaging ideas that will affect
a broad range of science and technology
fields, such as materials science, biological
imaging, nanolithography, and endoscopy.

As an illustrative example, an endo-
sopic “nanocamera” could instantan-
eously capture an image with thou-
sands of pixels with a resolution well
below the diffraction limit (much less
than λ/2 and possibly as small as λ/10
to λ/25). Near-field scanning optical
microscopy is an established scanning-
probe technique that uses a nanoscale
aperture and tapered fibers to achieve an-
approximately 40 nm resolution in the vis-
ible region of the spectrum. A nanocam-
era, in contrast, would not require
serial scanning, thus allowing for very
rapid imaging of structures that are diffi-
cult to image serially, such as living cells.

Other proposed concepts to image at
resolutions beyond the diffraction lim-
it include superlenses, coupled-sphere
waveguides, and resonantly excited surface-
plasmon polaritons in arrays of metal wires.²

Shvets, Trendafilov, Pendry, and Sarychev
propose an endoscopic nanocamera design con-
sisting of an array of metallic nanowires embed-
ded in a tapered optical fiber that can magnify
and demagnify an image (see Fig. 3).³ They
explain that if the taper cross section becomes
smaller than λ/4, then all the transverse electric
(TE) and transverse magnetic (TM) modes of the
light become evanescent. Therefore, the only propa-
gating modes are TEM modes that are transverse
local—in other words, an image of finite lateral
size does not disperse as it propagates along a uni-
form cylindrical fiber. In a tapered fiber, however,
the taper determines the magnification and demagnification (see Fig. 4). More-
over, the number of pixels in each camera
can number in the thousands per fiber for a real imaging application.

For perfectly electrically conducting metal wires, the TEM modes are dis-
personless with respect to any trans-
verse wavevector, and hence are trans-
verse local. In reality, this assumption is
true only for far-infrared and terahertz
wavelengths where real metals have very
low loss, and hence this tapered-fiber im-
aging scheme will work well for these
frequency ranges. However, in the mid-
to near-infrared and visible frequency
ranges, effects due to the excitation of
surface-plasmon polaritons (SPPs) be-
come an important consideration. Vary-
ing the metal wire height, diameter, and
relative spacings effectively tunes the SPP
resonances at different wavelengths. For
example, subwavelength imaging with a
resolution of 40 nm using a metallic silver
nanowire array (20 nm diameter, 50 nm
long, and spaced 40 nm apart in a hex-
agonal geometry) has been numerically modeled by Ono, Kato, and Kawata at
488 nm wavelength.² The Shvets proposal
FIGURE 4. Finite-difference time-domain simulation of a tapered nanocamera design shows the image of a small metal sphere (diameter approximately 2/25) magnified (top) and demagnified (bottom) by a factor of five. Camera dimensions used in the simulation are (in units of $L_C = \lambda/15$) base, $10 \times 10$ $L_C$ tip, $2 \times 2$ $L_C$ wire separation, $d = 3 L_C$ and wire diameter, $w = 2 L_C$. (Courtesy of G. Shvets)

lengths requires metal-wire radii that begin to approach the skin depth, which will result in crossover between wires. Thus, the Shvets concept is ideally suited for mid-infrared and longer wavelengths.

Finally, the taper itself provides a key advantage to the nanocamera idea, namely, that it magnifies the pixels in the image so that conventional silicon and germanium readout chips can detect them. If a typical photodetector pixel size is 5 µm, and an imaging resolution of 50 nm is desired, a magnification of 100 x is needed. Calculations by Shvets et al., show that a maximum taper slope of 45° is allowed before the crosstalk between wires causes image spreading. For gentler tapers, this is not an issue with the TEM-mode imaging. As yet, no obvious conventional method exists for fabricating a nanocamera such as Shvets and his colleagues describe. However, the high-pressure fiber-filling process is well suited for fabricating arrays of metal nanowires. Existing taper fabrication methods work on both conventional and microstructured optical fibers. Once the taper is constructed, the high-pressure filling process will facilitate ordered arrays of nanowires with a large range of different metals via suitable chemical-vapor deposition processes. Characterization of the light-guiding and imaging properties would then follow. The resulting endoscopic nanocamera would be useful for rapid nanoscale imaging over micron-square areas and would thus find application in areas ranging from biology and medicine to advanced materials research.

REFERENCES

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