Enhancing the performance of fiber-based sensors using plasmonic nanocrystals

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The plasmonic properties of metal nanocrystals deposited on surfaces can be fine-tuned to enhance the performance of novel sensing platforms based on tilted fiber Bragg gratings.

The development of simple, inexpensive, accurate, sensitive, and reliable platforms for use in security, environment, and biomedical sensing applications represents a challenging task. As a rule, high accuracy and reliability of detection require expensive equipment or the involvement of highly skilled operators. The challenge, therefore, is in creating a low-cost sensor with relative accuracy. Tilted fiber Bragg grating (TFBG) sensors offer certain advantages for this application. The most important among these advantages rely on the structural integrity and temperature insensitivity of the fiber. A high structural integrity greatly increases the reliability of the device, while temperature insensitivity eliminates the necessity for temperature-dependent calibration, thereby significantly decreasing running costs. We have demonstrated that the efficiency of TFBG sensors such as these can be further improved by coating the fiber with a thin metal layer. Surface waves inside this layer, called surface plasmon polaritons (SPP), can be excited by an external electromagnetic field, such as laser light. However, SPP-enhanced sensors such as these require very smooth and continuous gold films, which are not easy to prepare on a fiber.

To address this problem, we proposed a reliance on localized surface plasmon resonances (LSPR) instead of SPP. Unlike SPP, LSPR can be excited in nanometer-scale particles of gold or silver to support resonances at the wavelengths of interest. Our work showed that by depositing nanowires on the cladding surface of a TFBG sensor, the LSPR excitations cause the sensitivity of the TFBG resonances to the external refractive index to increase by a factor of 3.5, despite the low surface coverage of the nanowires (<14%).

Figure 1. Representative electron microscopic images of (a) silver nanocubes, (b) a gold nanocage, and (c) silver nanorods.

We further explored the effect of LSPR on different plasmonic nanocrystals (see Figure 1) and the performance of TFBG devices for sensing, particularly for the purpose of optical signal excitation in the visible spectral region. To enhance the sensor response when any wavelength is used, a plasmonic coating which supports resonances in the spectral region of interest—from visible...

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to near-infrared (NIR)—is required. This enables the sensor response to be enhanced for chosen wavelengths, giving the device more flexibility.

Broad spectral coverage becomes achievable when plasmonic nanocrystals are deposited on a solid support. For example, the plasmonic response for a monolayer of small (40nm) silver nanocubes deposited on a glass slide using the Langmuir Blodgett (LB) method is greatly affected by the surface pressure. Increasing the surface pressure decreases the inter-particle separation, which leads to stronger dipole-dipole coupling (DD) in plasmonic monolayers. In the UV-visible extinction spectra, this can be seen as a strong band at longer wavelengths: see Figure 2(a). As such, high-pressure silver nanocube monolayers can efficiently absorb light in the entire visible range. They, therefore, provide a suitable coating for TFBG devices operating in the visible region. A supported monolayer of gold nanocages with a width of ~40nm reveals a visible dipole LSPR at 700–800nm and a DD band at ~850nm—see Figure 2(b)—which makes this plasmonic coating suitable for operation in the NIR region. Similarly, a monolayer of sparsely deposited non-interacting silver nanorods is able to absorb NIR light by virtue of its longitudinal LSPR, as longitudinal resonances are excited at longer wavelengths.

Small angle tilting of the fiber Bragg grating enables effective diffraction of light from the fiber core into the cladding, for both backward- and forward-propagating core modes. This allows for the possibility of exciting cladding modes in such devices: see Figure 3(a). When visible light is coupled into a fiber with TFBG, the angles of diffraction are dependent on both grating and wavelength. A small fraction of the diffracted light radiates into free space with a cone-like geometry: see Figure 3(b). The intensity of this radiated light, however, is too weak for excitation of a secondary optical signal, since most of the energy is trapped in the waveguide in the form of cladding modes. To release as much light as possible from the fiber, we used a plasmonic nanocrystal coating. The cladding modes excite LSPR, which leads to the creation of ‘hot’ spots suitable for the excitation of optical signals from the molecules near the TFBG. The plasmonic coating acts as an antenna, broadcasting the light from the waveguide into free space. A TFBG coated with nanocrystals appears very different to bare TFBG. There is no directed light propagating away from the fiber in the cone-like geometry as seen previously. Instead, quasi-uniform diffuse ‘glowing’ of the TFBG is seen: see Figure 3(c).

Figure 2. Extinction spectra of (a) supported silver nanocubes with indicated surface pressure of the LB (Langmuir Blodgett) monolayer, (b) gold nanocages (top) and silver nanorods (bottom) on a glass slide. a.u.: Arbitrary units. DD: Dipole-dipole interaction. D: Dipole resonance. Q: Quadrupole resonance.

Figure 3. (a) The experimental setup, using a tilted fiber Bragg grating (TFBG) as a source of excitation. A fiber with a TFBG was cut and coated with an optically thick layer of gold (Au) to prevent light escaping from the fiber end, and to serve as a mirror reflecting light back. The TFBG was coated with a monolayer of silver nanocubes. The dye rhodamine 6G (Rh6G; 1μM) was used as a label for Raman spectroscopy. (b) Light propagation from a bare TFBG with a gold coated end. Light was coupled from left to right and is diffracted forward at two different angles. A symmetric pattern of diffracted light is created by the light reflected from the gold mirror. (c) The fiber shown in (b) coated with silver nanocube monolayer causes diffuse “glowing” of the TFBG.
We used the same setup for the detection of the surface enhanced Raman scattering (SERS) signal for a Raman active dye (rhodamine 6G). Unlike for the bare TFBG, we were able to detect the spectrum with an accumulation time of less than one minute. A unique excitation geometry is presented using this setup, since the entire $1\text{cm} \times 250\mu\text{m}$ surface of the TFBG coated with plasmonic nanocrystals can be used for the optical signal excitation and collection.

In summary, we demonstrated that the performance of TFBG-based devices can be improved with the use of plasmonic nanocrystal coatings. We proposed and demonstrated the use of a novel TFBG platform for optical signal excitation and successfully used the device for the detection of a rhodamine 6G SERS signal. Our next step is to optimize the nanoparticle density and to use TFBG for excitation of other optical signals, such as fluorescence.

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References