Optical sensors: from micro to nano and beyond

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The unique transmission properties of micro- and nanostructured materials, combined with mature fiber-optics technology, enable novel ultra-compact, multifunctional sensor arrays.

A plethora of novel applications in biology, chemistry, medicine, and defense would be possible if we could accurately detect, track, and identify targets in highly cluttered, dynamic environments.\(^1\) Compact, multimodal sensing capable of detecting multiple characteristics of the electromagnetic radiation or optical materials, such as intensity, phase, wavelength, polarization, or refractive index (see Figure 1), offers a potential way to do this. There has been tremendous progress in the field of optical sensors over the last decade, but despite this, there are still challenging issues that need to be solved. These include: ease of multiplexing; remote real-time monitoring with fast, label-free detection; ultra-compact size; and input/output coupling efficiency. While several modern optical platforms, such as fiber optics, plasmonics, and photonic bandgap structures, have been separately employed to develop various sensing devices, it is only recently that the tremendous advantages of combining them have been recognized.\(^2\)–\(^4\)

In our work, we employ the unique transmission properties of micro- and nanostructured materials, including photonic bandgap structures and optical metamaterials, combined with mature fiber-optics technology, to design and demonstrate several novel approaches to realizing ultra-compact, multifunctional sensor arrays. In particular, we are developing three new classes of sensors: antiresonant, reflecting, optical fiber-based refractometric and optofluidic devices; multi-color, highly directional photonic-bandgap-based sensor arrays; and polarization-sensitive devices based on fiber-coupled magnetic metamaterial structures (see Figure 2).

The first category of proposed sensor is based on photonic crystal fibers (PCFs), which are a new class of optical fibers containing air holes ranging in diameter from 25nm to 50\(\mu\)m. The air holes run along the fiber length, which could be as short as a few microns or as long as several kilometers, and are distributed in the cladding in either periodic or random fashion. PCF-based devices bring new degrees of freedom as their properties can be modified after the fiber has been made. For example, the air-holes can be filled with temperature sensitive fluids, liquid crystals, or other materials that change their optical properties in response to electric or magnetic fields, strain, or light intensity.

We have proposed, designed, and experimentally demonstrated a compact, all-fiber sensor, using unique spectral properties of PCF with localized high-index inclusions based on the wavelength shift of the transmission spectrum in response to the uniform or gradient refractive index change of the analyte for biomedical, chemical, and other applications (see Figure 2a).\(^5\)

We have also extended this platform to design a novel, compact biosensor that combines high detection sensitivity of antiresonant optical waveguide with optofluidic functionality. It enables compact and rapid processing of small biofluid samples (see Figure 2b). Such a combination leads to performance that meets or exceeds that of a number of proposed sensor technologies, and it has significant advantages, including ease of multiplexing and in- and out-coupling of light.\(^6\)

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Figure 2. (a) Examples of various proposed hybrid sensor technologies. Photonic crystal fiber-based sensor.\(^5\) (b) Optofluidic sensor.\(^6\) (c) Bull’s-eye sensor array. (d) Metamaterial-based sensor.\(^4\) 

The second approach is a design for a compact vertically-emitting sensor array based on submicron multi-ring photonic bandgap structures (Figure 2c). We used focused ion-beam etching, which enables precise dimensional control in the submicron range, to pattern these bull’s-eye structures inside a dye-doped xerogel (a type of porous material). We designed the structures to confine light at the fluorescence wavelength in the transverse direction using the photonic bandgap effect. In this way, when excited by a pump light source, the structure emits light in a cone that points perpendicular to the sensor surface. These vertical cavities can be functionalized by incorporating analyte-sensitive fluorescent molecules. In particular, the ability to direct the emission of each sensor array element, coupled with detection by a photodetector array, makes multi-color, highly directional, compact biological and chemical sensor arrays possible.

Finally, the third enabling technology is photonic metamaterials (MMs), which are artificial nanostructures that offer nearly unlimited opportunities to design materials with novel properties, such as positive, negative, and even zero indices of refraction. Recently, we have designed and demonstrated a fiber-coupled magnetic MM on the transverse cross-section of a single-mode optical fiber (see Figure 2d). In this way, it combines the advantages of fiber and MM technologies. Such fiber-MM integration provides new solutions for simultaneous measurements of several important parameters such as intensity, polarization, and spectral characteristics, which can lead to novel photonic-on-a-chip systems for multimodal sensing.

There is a need for compact, multimodal sensors. We have developed three classes of these sensors: antiresonant, reflecting, optical-fiber-based refractometric and optofluidic devices; multi-color, highly directional, photonic-bandgap-based sensor arrays; and polarization-sensitive devices based on fiber-coupled magnetic MM structures. We are now working toward demonstrating the advanced capabilities of these devices for specific applications.

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