Sensors based on silicon photonic crystal mirrors with engineered phase

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The reflected light from photonic crystal mirrors exhibits a phase shift that varies rapidly with wavelength, complicating design but also enabling new applications.

The miniaturization of optical systems introduces benefits similar to those for electronics, i.e., making fabrication efficient, simplifying packaging, and reducing cost. Scaling optics to smaller sizes presents a number of challenges, however. This is particularly true for optical sensors that are exposed to the environment. In such systems, the components must scale well, lend themselves to efficient parallel manufacturing, and be mechanically and chemically robust enough to perform reliably and with good long-term stability.

Mirrors are indispensable components in many optics applications. However, traditional mirror technologies do not perform well in miniaturized optical sensors. Metal mirrors are not sufficiently mechanically or chemically robust. This shortcoming complicates fabrication and packaging, and makes operation of the sensors in challenging environments impossible. Bragg mirrors consisting of multiple dielectric layers are sufficiently hardy for such applications, but do not scale well. The mirror thickness is determined by the desired wavelength and the required reflectivity, and thus cannot be reduced to fit the requirements of miniaturized systems.

Photonic crystal (PC) mirrors are simple devices that lend themselves readily to straightforward fabrication by standard integrated-circuit manufacturing technologies. In their simplest form, PCs consist of a plate of semiconducting material with a periodic array of holes: see Figure 1(a). The principle of PC operation is different from other mirror technologies because PCs depend on interference between different pathways. As illustrated in Figure 1(b), a plane wave incident on a PC has two available pathways for transmission: a direct path, as through a homogeneous plate; and an indirect path that involves coupling into and then back out of guided resonances. These two paths interfere with one another to establish the transmission and reflection spectra of the PC. In a correctly engineered PC mirror, the two pathways interfere destructively in transmission and constructively in reflection, leading to high reflectivity. Generally speaking, it is desirable to couple guided resonances with short lifetimes to create broadband reflection. Applications that require this narrowband response require coupling to long-lifetime guided resonances.

Because PC mirrors depend on their coupling to guided resonances, they store energy, which in turn means that they have a temporal delay (i.e., a phase shift). This is true for all mirrors. What make PC mirrors unique, however, is that they store more energy than traditional reflectors and do so in a single thin layer that makes up the PC. As a consequence of this, the phase response of PC mirrors varies rapidly with wavelength. An optical engineer therefore has the opportunity to design both the slope (i.e., the first derivative) and curvature (i.e., the second derivative) of the phase response.

Figure 1. (a) In its simplest form, a photonic crystal (PC) mirror is a high-index plate with a periodic array of holes. The array can be 2D, as shown here, or 1D, as in a high-index grating. (b) The high reflectivity of PC mirrors is caused by interference. Incident light is transmitted through the PC as a plane wave as well as through the excitation of guided resonances. These two pathways through the PC interfere and determine the reflection and transmission spectra.
One way to describe the slope of the PC phase shift is in terms of its ‘optical thickness,’ i.e., the distance from the mirror surface to the reflection plane. Consider a mirror with a phase response that decreases linearly with wavelength. Optically, this appears as if the reflection originates from a reflection plane below the mirror surface (i.e., because the propagation phase shift from the surface to the reflection plane and back would decrease with increasing wavelength). Conversely, a phase shift that increases with increasing wavelength would make it appear that the reflections originate from a reflection plane in front of the mirror surface. The interesting and ultimately useful (although initially frustrating) thing about PC mirrors is that their optical thickness can take a wide range of values, including negative ones.3, 4

Mirrors with specific curvature of their phase response have long been used for dispersion compensation, particularly in short-pulse lasers. The ability to also engineer the slope of the phase through PC mirrors opens up a large set of novel sensor applications, including ultrasensitive microphones, hydrophones, and pressure sensors, as well as sensors that are robust against laser instability, laser phase noise, and temperature fluctuations. Outside the field of optical sensors, flexible phase control could also enable the development of compact optical resonators with high quality factors and resonators that depend on anomalous Goos-Hänchen shifts.5 Some of these applications, e.g., stable ultra-sensitive Fabry-Perot sensors and novel resonator configurations, are already beginning to emerge, and additional undiscovered uses are sure to follow.

Due to their simplicity, robustness, and scalability, PC mirrors are ideal for miniaturized optical systems. Their phase response gives the optical designer flexibility to improve system performance and also enables a range of new applications.

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Olav Solgaard’s PhD research led to the establishment of Silicon Light Machines, and at UC Davis he created a multi-wavelength, fiber-optical switch that has been commercialized by several companies. His research interests include optical microelectromechanical systems, nanophotonics, optical sensors, microscopy, and dielectric electron accelerators.

References
5. Y.-P. Wong, X. Xiao, and O. Solgaard, Direct measurement of negative optical Goos-Hänchen shift from photonic crystal, CLEO. 2016. Paper FF2B.3