Photonic Crystal Guided-Mode Resonance Sensors for Optical Diagnostics

Moxtek has achieved low cost, wafer-scale manufacturing of plasmonic, photonic crystal, and hybrid structures and is ready to support your production needs, from developmental projects through commercialization. Potential applications for these structures include label-free biosensing, surface enhanced Raman spectroscopy (SERS), and microarray-based surface enhanced fluorescence sensing (SEFS).

1-D photonic crystal guided-mode resonance sensors

Grating-coupled, TiO_2 slab waveguides, also called guided mode resonance (GMR) filters, are a form of 1-D photonic crystal (PC) that gives a narrowband reflectance peak, which is sensitive to the local refractive index above the grating. The schematic and SEM cross section presented in Figure 1a-1b reveal the basic structure, which, when illuminated at specific resonant wavelengths, results in waveguiding and an enhancement of the near field intensity at periodic positions within and around the grating, as modeled in Fig. 1c. These PC-GMR structures can have large resonance quality factors with very narrow reflectance maxima and transmittance minima, whose positions are sensitive to both the angle of incidence and the local refractive index above the TiO_2 grating layer. This sensitivity to local refractive index allows for label-free sensing of local molecular binding events, such as those used in micro-array based bio-sensing assays. Some of the advantages of grating-based GMR sensors are given in Table 1 below.

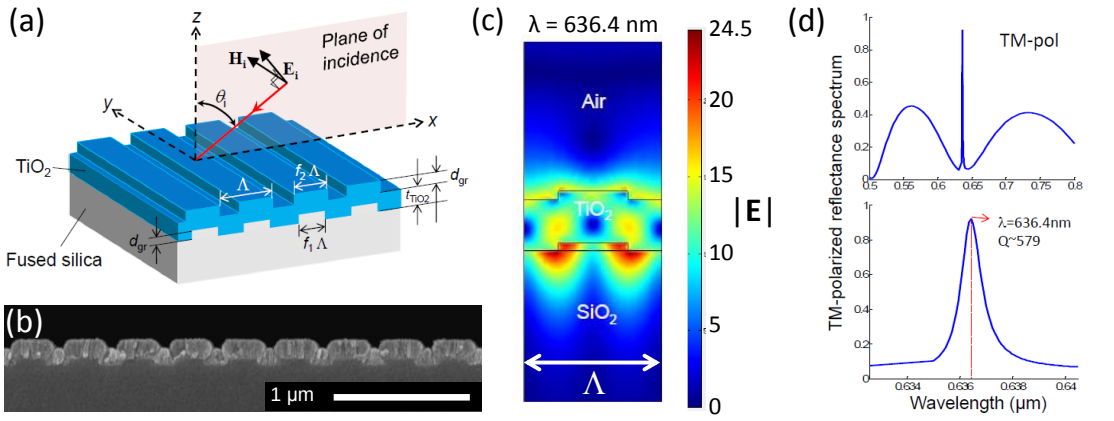

Figure 1. 1-D photonic crystal guided mode resonance (PC-GMR) sensor schematic, microstructure, and modeling results: (a) schematic (b) SEM cross-section, (c) optical model, revealing near-field enhancement and field confinement near the grating layer, and (d) optical modeling of narrow reflectance peak and high quality factor (Q).

Table 1: Advantages of Moxtek GMR sensors

- Low cost, high volume manufacturing
- Resonance wavelength easily tuned by changing grating pitch or angle of incidence
- Compatible with laser & broadband sources for
  - Spectral sensing (peak wavelength shift),
  - resonance angle based sensing, or
  - intensity-based sensing
- High quality factors and field strengths for:
  - enhanced fluorescence sensing, or
  - enhanced label-free sensitivity

Resulting in:

- Improved signal to noise ratios
- Faster response times and higher throughput
- Lower reagent volumes
- Low biosensor chip cost

PC-GMR sensor designs were fabricated with pitch varying from 360 - 410 nm, which allowed for spectral tuning of the resonance for label-free sensing and SEFS applications at various wavelengths. Wafer-scale optical metrology tools were used to map out GMR sensor reflectance uniformity, while chip-level measurement after dicing showed reasonable agreement with modeling. Resonance quality factors (Q) greater than 200 were observed, and could be controlled via grating fill factor (*f*), etch depth (d), and TiO_2 slab waveguide thickness (t).

The PC-GMR sensors were designed for measurement in air and showed a large shift (~2.5 nm) in resonance position after binding a self-assembled monolayer (SAM) to the TiO_2 waveguiding surface as a protein mimic to measure surface-sensing capability (Figure 2a). The same sensors also showed a reasonable shift (~0.3 nm) during *in-situ* label-free sensing underwater in a flow cell configuration (Figure 2b). Spectral sensitivity on the order of 0.03 nm has been demonstrated

using a similar GMR sensor design on a smartphone-based spectrometer.[1] Hence sub-monolayer detection limits for moderately sized molecules are possible in these GMR sensor systems for label-free detection of surface binding events. These SAM binding studies demonstrate the potential of these GMR filter designs for use as compact label-free sensors, which could be based on either spectral shift in resonance position, as demonstrated, or changes in intensity. Moxtek is now developing PC-GMR designs optimized for in-situ biosensing in aqueous environments. By monitoring the spectral transmittance or reflectance in a properly designed system, these 1-D photonic crystal GMR devices are sensitive enough for applications such as enzyme-linked immunosorbent assays (ELISA) and both DNA and protein microarrays.[1-4]

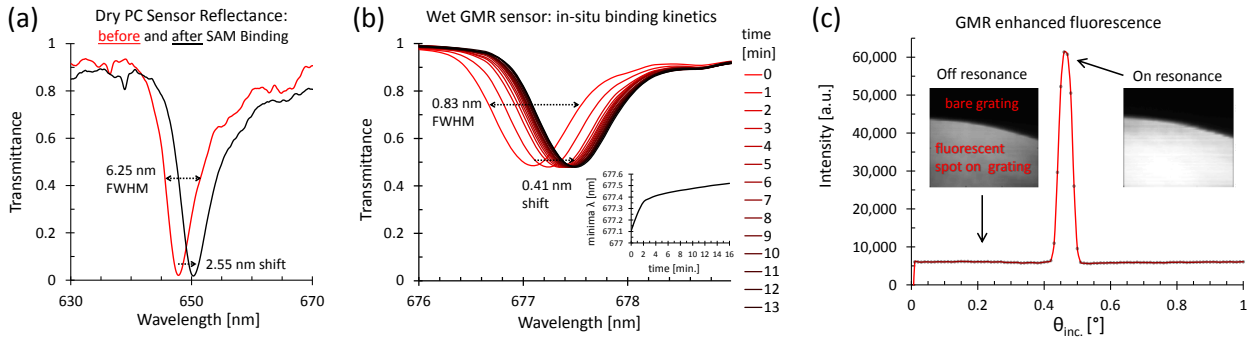

Figure 2. Proof-of-concept for PC-GMR sensing applications. (a)-(b) Label-free SAM binding studies using transparent PC-GMR sensors. (a) Dry measurements before and after monolayer binding. (b) Label-free binding kinetics in wet state (inset indicates position of minima vs. time). (c) GMR-enhanced fluorescence intensity vs. excitation angle after spotting, showing ten-fold enhancement.

Greater than ten-fold fluorescence intensity enhancement was also demonstrated (Fig. 2c) for a dye layer absorbed to the surface of a filter when the excitation angle was tuned to match the GMR condition. The insets depict line-scan fluorescence images taken at the edge of the dye layer at angles of 0.46° (on resonance) and 2.0° (off resonance). By optimizing the coating and density of binding sites above the TiO_2 grating, and by tuning the PC-GMR design to enhance both laser excitation and fluorescence emission (utilizing TM *and* TE resonances), between 60 - 328 fold improvement in fluorescence detection sensitivity and 41-42x increase in signal-to-noise ratio have been demonstrated when compared to a reference slide.[4-5] Preliminary efforts to utilize these PC-GMR structures as micro-array substrates for IgG, IgM, IgA, and Streptavidin-Biotin assays, which used a commercial spotter and fluorescence scanner, have shown the PC-GMR substrates to have average enhancements factors (fluorescence signal minus local background) of 7.7 and 21.9 when compared to glass and silicon reference slides that underwent the same surface preparation and assay protocols. It should be noted that the commercial scanner utilized was not optimized for readout of these photonic crystal structures, which ideally would utilize a well-controlled illumination angle for the excitation light source, as demonstrated in Fig. 2(c).

Conclusions

A label-free PC-GMR biosensor showed ~2.5 nm shift in resonance position after monolayer binding. Another PC-GMR design was developed for microarray-based SEFS and results from a non-optimized commercial scanner and non-optimized assay protocols produced ~8-22x signal enhancement when compared to reference slides. Furthermore, proper excitation source coupling was shown to produce better than ten-fold enhancement of the fluorescence signal, which should lead to improved assay sensitivity with further substrate and scanner optimization.

References

[1] Gallegos, D., et al., "Label-free biodetection using a smartphone," Lab Chip 13, 2124-2132 (2013).

[2] Choi, C.J., et al., "Comparison of label-free biosensing in microplate, microfluidic, and spot-based affinity capture assays," Analytical Biochemistry 405, 1-10 (2010)

[3] Cunningham, B.T., "Photonic Crystal Surfaces as a General Purpose Platform for Label-Free and Fluorescent Assays," JALA 15, 120-135 (2010).

[4] Block, I.D., et al., "A detection instrument for enhanced fluorescence and label-free imaging on photonic crystal surfaces," Optics Express 17, 13222-13235 (2009).

[5] Mathias, P.C., Wu, H.-Y., Cunningham, B.T., "Employing two distinct photonic crystal resonances to improve fluorescence enhancement," APL 95, 021111 (2009).

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