Optical waveguide biosensors constructed with subwavelength gratings

Jenq-Nan Yih, Yi-Ming Chu, Yen-Chieh Mao, Wei-Han Wang, Fan-Ching Chien, Chun-Yu Lin, Kuang-Li Lee, Pei-Kuen Wei, and Shean-Jen Chen

The reflection resonance spectrum of a subwavelength diffraction-grating-coupled waveguide is used to analyze biomolecular interactions in real time. By detecting this resonance wavelength shift, the optical waveguide biosensor provides the ability to identify the kinetics of the biomolecular interaction on an on-line basis without the need for extrinsic labeling of the biomolecules. A theoretical analysis of the subwavelength optical waveguide biosensor is performed. A biosensor with a narrow reflection resonance spectrum, and hence an enhanced detection resolution, is then designed and fabricated. Currently, the detection limit of the optical waveguide sensor is approximately $10^{-5}$ refractive-index units. The biosensor is successfully applied to study of the dynamic response of an antibody interaction with protein G adsorbed on the sensing surface. © 2006 Optical Society of America


1. Introduction

The development of biochips for biomolecular interaction analysis has proved to be a crucial enabling technology in permitting the progression of genomic study to proteomic study. These biochips provide powerful tools that are capable of detecting not only the interactions of relatively massive genes but also those of tiny biomolecules. Conventional biomolecular analysis techniques generally rely on some form of fluorescence detection technique. However, such detection systems require fluorescence labeling, a process that is both tedious and complex. Furthermore, the fluorescence level of the labeled biomolecules inevitably declines over time. Finally, these systems struggle to identify the kinetic information related to molecular interactions. Therefore label-free examination methods are highly attractive and merit further study.

The abnormal reflection phenomenon exhibited by a grating was discovered by Wood in 1902. Since then, many theoretical and experimental methods have been proposed for investigating the various types of diffraction grating structure. Yariv and Nakamura and Yariv and Yeh explored and extended periodic thin-film waveguide theory and its applications, including modal solutions, optical filters, and distributed-feedback lasers. Tiefenthaler and Lukosz demonstrated a waveguide diffraction-grating structure for optical switching and gas sensing and later analyzed the sensitivity of the diffraction-grating structure when it is used to probe for biochemical molecules. Exploiting the polarization selectivity of unidimensional diffraction gratings, Magnusson and Wang applied a resonance waveguide diffraction-grating structure, also known as a guided-mode resonance filter, to polarized light filtering and electro-optic switching. In 1996 Peng and Morris extended the theory of unidimensional diffraction-grating structures to their two-dimensional counterparts. These subwavelength diffraction-grating waveguides are known by many other names, including guided-mode resonance subwavelength gratings, resonant waveguide gratings, and resonant grating waveguides.

Cunningham et al. applied a two-dimensional diffraction-grating structure to the detection of biochemical molecules and achieved a resolution of...
approximately 10 mm in diameter led to simultaneous
illumination of more than 2500 spots on a glass plate of approximately 10 mm × 10 mm, thereby satisfying
the requirements of high-throughput screening.

The authors gratefully acknowledge the financial
support provided to this study by the Ministry of
Education and the National Science Council (NSC
93-212—M-006-006) of Taiwan; Additionally, the
support provided by the Center for Micro/Nano Tech-
ology Research, National Cheng Kung University, is
much appreciated.

5. Conclusions

The resonance wavelength shift of the subwave-
length grating-coupled waveguide proposed in this
study facilitates the dynamic on-line identification of
biomolecular interaction without the need for extrin-
sic labeling. Having first performed the theoretical
analysis and design of a subwavelength optical
waveguide biosensor, we fabricated a biosensor with
a narrow reflection resonance wavelength spectrum
and hence an improved wavelength-detection resolu-
tion. Integrating the subwavelength grating-coupled
waveguide sensor with a compact normally incident
spectroscopy, we identified a detection limit of ap-
proximately 10−5 RIU during the testing of several
buffer solutions. Furthermore, the dynamic response
of an antibody interacting with protein G adsorbed
on the sensing surface of the biosensor has been success-
fully observed. Compared with the use of a collimated
white-light beam, using an objective lens to condense
the white light onto the chip preserves the signal-to-
noise ratio of the detection. Therefore, adjusting the
imaging field aperture to limit the effective chip scope
to less than 100 µm in diameter led to simultaneous
illumination of more than 2500 spots on a glass plate
of approximately 10 mm × 10 mm, thereby satisfying
the requirements of high-throughput screening.

The authors gratefully acknowledge the financial
support provided to this study by the Ministry of
Education and the National Science Council (NSC
93-212—M-006-006) of Taiwan; Additionally, the
support provided by the Center for Micro/Nano Tech-
ology Research, National Cheng Kung University, is
much appreciated.

Fig. 6. Dynamic response of antibody interaction with protein on
a sensing surface. Numerals 1–9 on the curve indicate injection of
the correspondingly numbered targets into a fluid cell.

References

of light in a diffraction grating spectrum,” Phil. Mag. 4, 396–408
(1902).
2. A. Hessel and A. A. Oliner, “A new theory of Wood’s anomalies
3. D. C. Flanders, H. Kogelnik, R. V. Schmidt, and C. V. Shank,
dielectric waveguides,” IEEE Trans. Microwave Theory Tech. 23,
123–133 (1975).
5. S. T. Peng, “Rigorous formulation of scattering and guidance
by dielectric grating waveguides: general case of oblique inci-
7. M. G. Moharam and T. K. Gaylord, “Rigorous coupled-wave
analysis of grating diffraction—E-mode polarization and
8. P. Sheng, R. S. Stepleman, and P. N. Sanda, “Exact eigenfunc-
tions for square-wave gratings: application to diffraction and
(1982).
waveguide structures,” IEEE J. Quantum Electron. 33,
10. A. Yariv and M. Nakamura, “Periodic structures for integrated
11. A. Yariv and P. Yeh, Optical Waves in Crystals: Propagation
12. K. Tiefenthaler and W. Lukosz, “Integrated optical switches and
as integrated-optical chemical sensors,” J. Opt. Soc. Am. B 6,
15. S. Peng and G. M. Morris, “Resonant scattering from two-
16. S. Peng and G. M. Morris, “Experimental demonstration of
resonant anomalies in diffraction from two-dimensional grat-
17. B. Cunningham, P. Li, B. Lin, and J. Pepper, “Colorimetric
resonant reflection as a direct biochemical assay technique,”
(2000).
free highly sensitive detection of (small) molecules by wave-
length interrogation of integrated optical chips,” Sensors
theory of zeroth-order lamellar gratings in conical mountings,”
theory of two-dimensional subwavelength gratings in the non-