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Analysis for an Improved Nanomechanical Microcantilever Sensor on Optical Waveguides

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ABSTRACT An analysis model for an optical waveguide microcantilever sensor is developed combining the optical and mechanical models. An improved optical waveguide microcantilever sensor with a buffer is provided and taken as an example to explore using the analysis model. A systematic and detailed discussion about the couplers for the input waveguide to optical waveguide cantilever and the optical waveguide cantilever to the output waveguide of the improved waveguide cantilever sensor is presented. The sensitivity of an improved optical waveguide cantilever sensor is evaluated by analyzing the input/output waveguide, buffer, microcantilever, and gap. An improved optical waveguide microcantilever sensor by adding a buffer shows a sensitivity of $5.7 \times 10^{-4} nm^{-1}$, which is improved by 51.3%, compared with a conventional optical waveguide microcantilever sensor. The design of an optical waveguide cantilever sensor is a trade-off of different design parameters. These will be helpful for the study of an optical waveguide cantilever sensor.

INDEX TERMS Optical waveguide cantilever, buffer, analysis model.

I. INTRODUCTION

Nano-mechanical sensors [1] have become paramount tools as transducers for highly sensitive biomolecule detection, such as viruses [2], proteins [3], cancer cells [4], and small molecules [5]–[7]. It performs real-time detection and readout by changing the mechanical behavior of the transducer. As a kind of nanomechanical sensors, integrated optical waveguide microcantilever-based sensors have received increasing attention [8]–[11] due to the advantages of high sensitivity, small size and easy integration for multiple detection [12]–[15]. In an optical waveguide cantilever sensor, the optical waveguide cantilever (OWC) works for the mechanical response generation and light propagation as an optical waveguide, the sensor detects the mechanical response by observing the output optical power of the optical waveguide cantilever with different bending displacements in return [13]. As a relatively new nanomechanical cantilever sensor, the researchers focus on the material of the optical waveguide microcantilever sensors to improve the performance [16]–[21]. However, few detailed analysis has been performed for the nanomechanical microcantilever sensors on optical waveguides.

In this paper, a detailed analysis of nanomechanical microcantilever sensors on optical waveguides was developed using mechanical and optical models. A finite-element method (FEM) was employed to analyze the nanomechanical microcantilever sensors. We took an improved optical waveguide cantilever system [22] as an example to explore the analysis. Following this introduction, in Section II, the principle of the optical waveguide cantilever sensor was presented, the model for the optical waveguide cantilever was developed. Section III provided a discussion about the results and their comparison with the conventional structure. The conclusion was described in Section IV.

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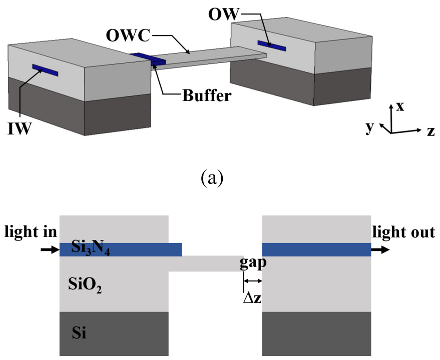
II. THEORY

The overall structure of an improved optical waveguide cantilever sensor [22] is depicted in Fig.1, which is comprised of an input waveguide (IW), a buffer, an optical waveguide microcantilever (OWC) and an output waveguide (OW). The IW and OW are grown on the silicon substrate by the silicon nitride($n_{Si_3N_4} = 2.0$) core and silicon oxide($n_{SiO_2} = 1.46$) cladding. The buffer is formed by extending the IW to OWC.



(b)

FIGURE 1. The structure of an improved optical waveguide microcantilever sensor: (a) 3D view, (b) lateral view.

The optical waveguide microcantilever sensor works on the dependence of the coupling efficiency between waveguides with their misalignment concerning each other. The light emitted by the laser after propagating through the input waveguide is coupled into the buffer, which can reduce the scattering loss and increase the coupling efficiency [22]. Then, light from the buffer couples into OWC. Finally, light exiting the OWC free-end is captured by OW through a gap distance. The optical power captured by OW will vary with the change of free-end displacement of the OWC in the vertical direction. Therefore, high sensitivity detection of the OWC deflection can be acquired with high integration.

The measurement of OWC chip with several cantilevers is based on a single laser-single acquisition channel in order to evaluate the optical response of each cantilever. A microfluidic cell is needed to integrate the OWC chip with a flow cell enabling reagents to be introduced to the cantilevers in a reproducible way, and subsequently removed to waste. The OWC chip, mounted with the microfluidic cell, is placed between the light source and the acquisition photodiode system. The microfluidic cell is mounted on a motorized single axis platform to select the microcantilever to be evaluated or to perform a sequential detection of the response of several microcantilevers in the OWC chip [23].

Sensitivity is the primary determinant to evaluate an optical waveguide cantilever sensor, which can be improved by enhancing the mechanical deflection and reducing the optical losses for the coupling from IW to OWC and OWC to OW. The analysis model of an optical waveguide cantilever sensor should include the mechanical and optical models.

A. OPTICAL MODEL

In order to increase the sensitivity of an optical waveguide cantilever sensor, the OWC should be single-mode in the vertical direction [24]. The modes are the form of light propagation in the optical waveguide. The single-mode OWC in the vertical direction is decided by the relationship between the effective refractive index and the mode, which can be obtained from the eigenvalue equation for the asymmetric planar waveguides in transverse electric(TE) modes [25]:

$$V\sqrt{1-b} = m\pi + tan^{-1}\sqrt{\frac{b}{1-b}} + tan^{-1}\sqrt{\frac{b+a}{1-b}} \quad (1)$$

where V is the normalized waveguide thickness, b is the normalized waveguide refractive index, a is the asymmetric of the waveguide, m is the order of light guided mode.

The optical-sensitivity is defined as the derivative of the coupling efficiency from OWC to OW across the gap and the bending displacement of the OWC [23]:

$$Sens = \frac{\partial \Gamma}{\partial x} \quad (2)$$

where Γ is the coupling efficiency from OWC to OW.

The coupling efficiency between waveguides can be calculated using the overlap integral [26]:

$$\Gamma(x, \Delta z) = \frac{(\int_{-\infty}^{\infty} E_g(x, \Delta z)E_y^*(x)dx)^2}{\int_{-\infty}^{\infty} E_g(x, \Delta z)E_g^*(x, \Delta z)dx \int_{-\infty}^{\infty} E_y(x)E_y^*(x)dx} \quad (3)$$

where $E_g(x, \Delta z)$ is the electric field distribution of the light exiting the OWC at the distance of Δz, and $E_y(x)$ is the distribution of the electric field of the output waveguide. In this study, only vertical direction deflection of the waveguides in TE mode is considered.

B. MECHANICAL MODEL

The mechanical bending of OWC is another influence on the sensitivity. The OWC is initially suspended horizontally and its surface serves as the functional area. The surface stress $\Delta\delta$ occurs when molecules interacts on the surface of the OWC, which ultimately leads to the bending deflection [24], [27]:

$$\Delta y \approx \frac{3K(1-\nu)}{E}(\frac{Lc}{Tc})^2 \Delta\delta \quad (4)$$

where K is a constant that depend on the OWC material and geometric characteristics, ν is the Poisson ratio, E is the Young modulus, Lc and Tc are the OWC length and thickness respectively.

III. RESULTS AND DISCUSSION

Based on (1)-(4), a finite element method was executed for the analysis of an improved optical waveguide microcantilever sensor.The analysis model for an optical waveguide microcantilever sensor was combined by the optical and mechanical models. The FEM [28] is chosen as the numerical method, which is suitable for the complicated waveguide structures and also applicable to the stress analysis of optical waveguides. In the FEM, the domain of the problem is discretized into small elements. The solution is approximated in each element and it is connected at the nodal points to form the solution model in the entire analysis domain. A simple form of function is adopted to approximate the field in each element. The possible error in the solution is alleviated by increasing the number of elements and thus reducing the element size. All of the element contributions to the system are assembled to form the functional. The functional essentially consists of the field values at the nodes and boundary conditions at the peripheral nodes; that is, n-th order linear simultaneous equations are obtained. The solutions of the simultaneous equations give the unknown field values to be determined. Therefore, FEM is applicable to the complicated domain structures. In the simulation, the optical wavelength was 660 nm.

A. THE EVALUATION OF THE COUPLERS FOR IW TO OWC AND OWC TO OW

The working principle of the sensor was based on the coupling between the waveguides. The sensor included two couplers of IW to OWC and OWC to OW. The sensor was symmetrical for IW stage and OW stage. The structure of IW was same with OW.

The light from the laser is coupled into the IW. Compared with the multi-mode, IW in single mode has lower losses for the optical propagation. The effective refractive indices with the thickness of IW/OW are shown in Fig.2(a) for m = 0, 1, and 2. It can be observed that the thickness of IW/OW should be less than 230 nm for single-mode working. The coupling between IW and OWC was also evaluated as shown in Fig.2(b), IW/OW thickness should be smaller as possible for less optical losses. However, thinner IW has poor coupling with the fiber of an input laser. Considering the fabrication technology, we designed the thickness of IW and OW to be 80 nm.

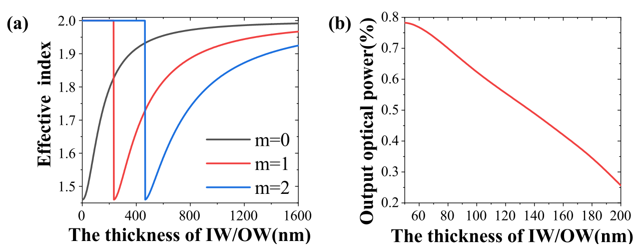


FIGURE 2. (a) The effective indices with the thickness of IW/OW. (b)The output optical power at the end of the OWC with the IW thickness.

In the coupler of IW to OWC as shown in Fig.1, a buffer by extending the IW is added to reduce the scattering loss by mitigating changes of the optical mode. Fig.3 shows the optimal buffer length of minimal coupling losses with the thickness of OWC. One can see that the buffer length is decided by the thickness of OWC. The optical coupling mode is tranformed at the connection of IW and OWC. As the

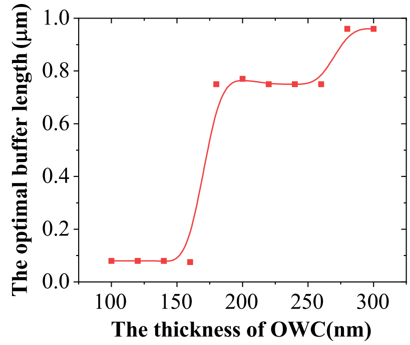


FIGURE 3. The optimal buffer length for the minimal coupling losses at different OWC thickness.

increase of the OWC thickness intensified the coupling transition, the longer buffer is needed to alleviate this transition. However, the buffer cannot be too long, or it will affect the mechanical response of the OWC.

The light is coupled to the OWC after passing through the buffer. The OWC was evaluated based on the coupling of IW to OWC. The output power at the end of OWC with the thickness of OWC is shown in Fig.4 for three modes (m = 0, 1 and 2) with the IW thickness of 80 nm, 140 nm, and 200 nm. One can observe that the cut-off thickness of OWC is 300 nm for the 1st mode and 600 nm for the 2nd mode. For higher sensitivity, the OWC must be single mode in the vertical direction. Hence, the OWC thickness should be smaller than 300 nm. Actually, thinner OWC means higher sensitivity. However, too thin waveguides are difficult to support its weight and fabricate. The OWC thickness of 200-300 nm will be desirable for the design of an optical waveguide cantilever sensor. Also, it can be seen that a thinner input waveguide indicates better coupling to the OWC. Fig. 4(b) indicates the electric field distribution for the OWC thickness of 200 nm, 500 nm, and 800 nm. It is obvious that the thickness of 200 nm has better optical propagation.

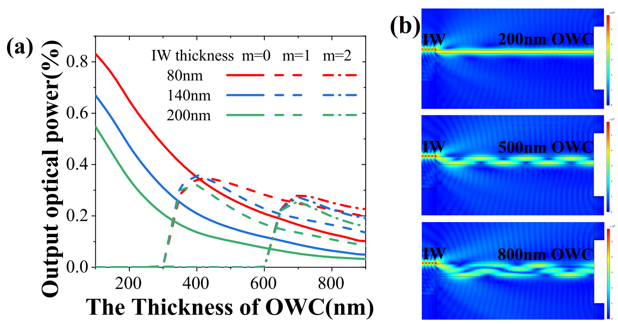


FIGURE 4. (a) The output optical power of OWC varies with its thickness under different IW thickness.(b)The electric field distribution of the sensor with the OWC thickness of 200 nm, 500 nm, and 800 nm.

After propagating in the OWC, the light travels through a gap and will be captured by OW. The gap has a direct impact on the sensitivity. The relationship of the gap with the output power captured by OW is shown in Fig.5 for the OWC

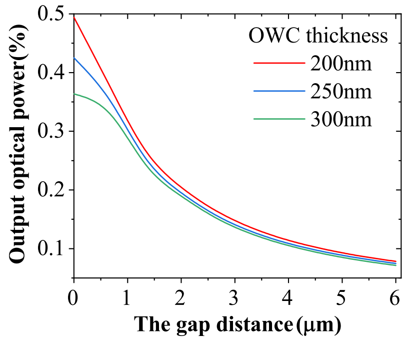


FIGURE 5. The output optical power of OW with the gap distance.

thickness of 200 nm, 250 nm, and 300 nm. The light captured by the OW is reduced with the gap distance because it faded away quickly in the transversal direction after leaving the end of the OWC. Smaller gap or thinner thickness of OWC has better output power efficiency. This means better sensitivity.

B. THE PERFORMANCE OF AN IMPROVED NANOMECHANICAL WAVEGUIDE MICROCANTILEVER SENSOR

In essence, the principle of the sensor is depended on the bending of OWC. In the detection process, the OWC would bend by surface stress, a mechanical model was used to simulate the deflection of OWC. The bending displacement of different forces $F(N)$ under the uniform-load is plotted in Fig.6. It is obvious that longer and thinner OWC always has better bending displacement.

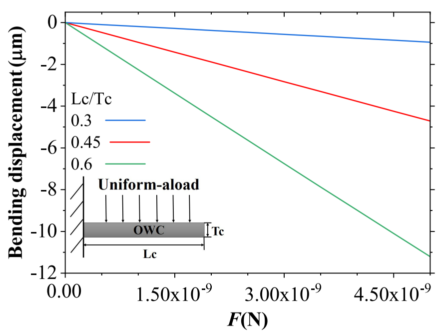


FIGURE 6. The bending displacement at the end of the OWC with different forces $F(N)$ under the uniform-load for Lc/Tc (OWC length to thickness) of 0.3, 0.45 and 0.6.

Based on Eq.2, the optical sensitivity is decided by the coupling efficiency of OWC through the gap to OW. The sensitivity was obtained by calculating the derivative of the coupling efficiency and deflection displacement. The coupling efficiency is a crucial bridge for the design of the structure and optical sensitivity. Fig.7 shows the coupling efficiencies and the sensitivities for OWC thicknesses(Tc) of 200 nm and 300 nm with and without a buffer under various bending deflections, respectively. The results without the buffer are consistent with previous research [13], which means that our model are effective.

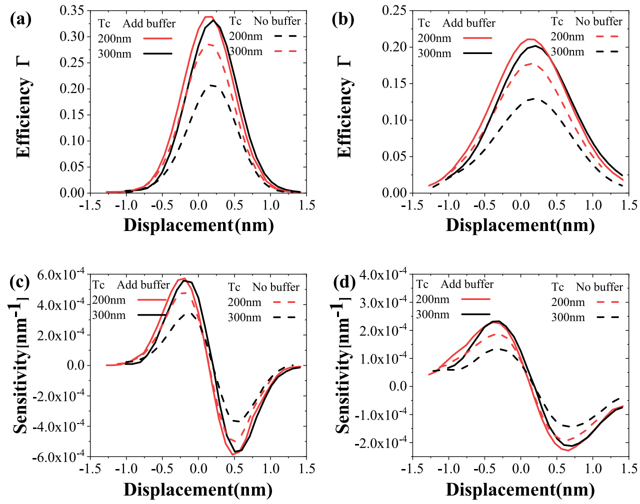


FIGURE 7. The coupling efficiency of optical waveguide cantilever sensors with and without a buffer for (a) gap of 1 μm and (b) gap of 2 μm. The sensitivity for (c) gap of 1 μm and (d) gap of 2 μm.

One can observe that the increase of gap distance and the OWC thickness is accompanied by the decrease of the coupling efficiency and the sensitivity. Actually, too short gap distance or too thin OWC are difficult to achieve in the actual production. Therefore, the gap distance of 1μm and 2μm, the OWC thickness of 200nm and 300nm are selected for the analysis. More importantly, one can find that an optical waveguide cantilever sensor with a buffer can obviously increase the efficiency and the sensitivity, compared with a conventional sensor without a buffer. For 300 nm-thick OWC and 1μm gap, the sensitivity can be increased by 51.3 %. The results indicate that the detection performance of the sensor can be improved by adding the buffer.

IV. SUMMARIZES

In this paper, an analysis model for an optical waveguide microcantilever sensor was developed. An improved optical waveguide microcantilever sensor was taken as an example to explore the analysis model. The IW/OW was discussed, thinner IW/OW had better coupling with OWC, but poorer coupling with the fiber of a laser, an 80 nm-thick IW/OW was chosen as a compromise considering the fabrication technology. The buffer of an improved optical waveguide sensor was analyzed, the optimal buffer length for different OWC thickness was presented. The optical waveguide microcantilever was studied, thinner and longer OWC was always desirable, however, too thin OWC was difficult to support its weight and fabricate. In a word, our analysis showed that an optical waveguide microcantilever sensor with a buffer can improve the performance, compared with a conventional waveguide sensor without a buffer. The design of an optical waveguide microcantilever sensor was a trade-off for different factors.

REFERENCES

[1] L. G. Carrascosa, M. Moreno, M. Álvarez, and L. M. Lechuga, "Nanomechanical biosensors: A new sensing tool," *TrAC Trends Anal. Chem.*, vol. 25, no. 3, pp. 196–206, Mar. 2006.

[2] G. Longo, L. Alonso-Sarduy, L. M. Rio, A. Bizzini, A. Trampuz, J. Notz, G. Dietler, and S. Kasas, ''Rapid detection of bacterial resistance to antibiotics using AFM cantilevers as nanomechanical sensors,'' *Nature Nanotechnol.*, vol. 8, no. 7, pp. 522–526, Jul. 2013.

[3] M. Yue, J. C. Stachowiak, H. Lin, R. Datar, R. Cote, and A. Majumdar, ''Label-free protein recognition two-dimensional array using nanomechanical sensors,'' *Nano Lett.*, vol. 8, no. 2, pp. 520–524, Feb. 2008.

[4] T. Kwon, S. Gunasekaran, and K. Eom, ''Atomic force microscopy-based cancer diagnosis by detecting cancer-specific biomolecules and cells,'' *Biochimica Et Biophysica Acta (BBA) Rev. Cancer*, vol. 1871, no. 2, pp. 367–378, Apr. 2019.

[5] J. Fritz, M. Baller, H. Lang, H. Rothuizen, P. Vettiger, E. Meyer, H.-J. Güntherodt, C. Gerber, and J. Gimzewski, ''Translating biomolecular recognition into nanomechanics,'' *Science*, vol. 288, no. 5464, pp. 316–318, 2000.

[6] G. Zhang, C. Li, S. Wu, and Q. Zhang, ''Label-free aptamer-based detection of microcystin-LR using a microcantilever array biosensor,'' *Sens. Actuators B, Chem.*, vol. 260, pp. 42–47, May 2018.

[7] C. Li, G. Zhang, S. Wu, and Q. Zhang, ''Aptamer-based microcantilever-array biosensor for profenofos detection,'' *Analytica Chim. Acta*, vol. 1020, pp. 116–122, Aug. 2018.

[8] M. Serene, R. Babu, and Z. C. Alex, ''Sensitivity analysis of micro-mass optical MEMS sensor for biomedical IoT devices,'' in *Internet of Things and Personalized Healthcare Systems*. Singapore: Springer, 2019, pp. 1–12.

[9] H. P. Lang, M. Hegner, and C. Gerber, ''Nanomechanical cantilever array sensors,'' in *Springer Handbook Nanotechnology*. Berlin, Germany: Springer, 2017, pp. 457–485.

[10] P. G. Gopinath, V. R. Anitha, and S. A. Mastani, ''Microcantilever based biosensor for disease detection applications,'' *J. Med. Bioeng.*, vol. 4, no. 4, pp. 307–311, 2015.

[11] F. S. Ligler and C. R. Taitt, *Optical Biosensors: Today and Tomorrow*. Amsterdam, The Netherlands: Elsevier, 2011.

[12] K. Zinoviev, C. Dominguez, J. A. Plaza, and L. M. Lechuga, ''Optical waveguide cantilever actuated by light,'' *Appl. Phys. Lett.*, vol. 92, no. 1, 2008, Art. no. 011908.

[13] D. Fariña, M. Álvarez, S. Márquez, C. Dominguez, and L. M. Lechuga, ''Sensitivity analysis for improving nanomechanical photonic transducers biosensors,'' *J. Phys. D, Appl. Phys.*, vol. 48, no. 33, Aug. 2015, Art. no. 335401.

[14] A. Mostafazadeh, G. G. Yaralioglu, and H. Urey, ''Optical fiber array based simultaneous parallel monitoring of resonant cantilever sensors in liquid,'' *Sens. Actuators A, Phys.*, vol. 242, pp. 132–139, May 2016.

[15] X. Yu and R. Zhao, ''Biochemical sensors based on piezoresistive microcantilevers,'' in *Micro Electro Mechanical Systems*. Singapore: Springer, 2018, pp. 689–716.

[16] R. Mathew and A. R. Sankar, ''A review on surface stress-based miniaturized piezoresistive SU-8 polymeric cantilever sensors,'' *Nano-Micro Lett.*, vol. 10, no. 2, p. 35, Apr. 2018.

[17] S. Stassi, E. Fantino, R. Calmo, A. Chiappone, M. Gillono, D. Scaiola, C. F. Pirri, C. Ricciardi, A. Chiadò, and I. Roppolo, ''Polymeric 3D printed functional microcantilevers for biosensing applications,'' *ACS Appl. Mater. Interfaces*, vol. 9, no. 22, pp. 19193–19201, Jun. 2017.

[18] K. Noda, K. Hoshino, K. Matsumoto, and I. Shimoyama, ''A shear stress sensor for tactile sensing with the piezoresistive cantilever standing in elastic material,'' *Sens. Actuators A, Phys.*, vol. 127, no. 2, pp. 295–301, Mar. 2006.

[19] P. Wang, A. Michael, and C. Y. Kwok, ''Silicon waveguide cantilever displacement sensor for potential application for on-chip high speed AFM,'' *Frontiers Optoelectron.*, vol. 11, no. 1, pp. 53–59, Mar. 2018.

[20] V. Seena, A. Rajorya, P. Pant, S. Mukherji, and V. R. Rao, ''Polymer microcantilever biochemical sensors with integrated polymer composites for electrical detection,'' *Solid State Sci.*, vol. 11, no. 9, pp. 1606–1611, Sep. 2009.

[21] M. Vinchurkar, A. Joshi, S. Pandey, and V. R. Rao, ''Polymeric piezoresistive microcantilevers with reduced electrical variability,'' *J. Microelectromech. Syst.*, vol. 24, no. 4, pp. 1111–1116, Aug. 2015.

[22] Y. Jing, G. Fan, R. Wang, Z. Zhang X. Cai, J. Wei, X. Chen, H. Li, and Y. Li, ''Improved optical waveguide microcantilever for integrated nanomechanical sensor,'' *Sensors*, vol. 19, no. 19, p. 4346, 2019.

[23] E. D. F. Santana, ''Desarrollo de un sisetma biosensor opto–mecánico basado en cantilevers,'' Ph.D. dissertation, Univ. de Microelectrónica Aplicada, Univ. de Las Palmas de Gran Canaria, Gran Canaria, Spain, 2014.

[24] M. Tenje, ''Integrated optical read-out for polymeric cantilever-based sensors,'' Ph.D. dissertation, MIC-Dept., Micro Nanotechnology, Tech. Univ. Denmark, Kongens Lyngby, Denmark, 2007.

[25] G. Fan, Y. Li, C. Hu, L. Lei, and H. Li, ''Numerical study on an optical waveguide cantilever sensor,'' *J. Nanophotonics*, vol. 11, no. 2, May 2017, Art. no. 026007.

[26] R. G. Hunsperger, *Integrated Optics*, vol. 4. Berlin, Germany: Springer, 1995.

[27] J. E. Sader, ''Surface stress induced deflections of cantilever plates with applications to the atomic force microscope: Rectangular plates,'' *J. Appl. Phys.*, vol. 89, no. 5, pp. 2911–2921, Mar. 2001.

[28] K. Okamoto, *Fundamentals of Optical Waveguides*. New York, NY, USA: Academic, 2006.

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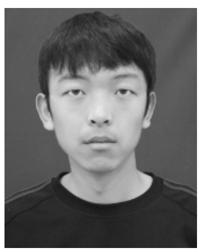

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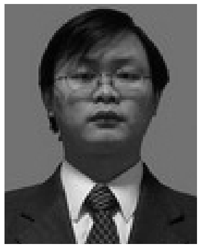

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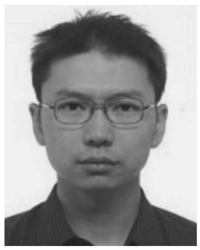

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