

Fabrication of fiber grating by phase mask and its sensing application

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This paper reports an investigation of a fabricated fiber grating device characteristics and its applications, using a phase mask writing technique. The phase mask technique used for writing fiber gratings has the advantages over the traditional holographic method because of its simpler writing setup and more reproducible characteristics. Specifically, the utilization of phase mask relaxes the strict requirement on the coherence of a UV light source. On the other hand, to photo induce an index change in the fiber core, light absorption must somehow occur. Alkins measured the absorption spectrum in a standard germanium doped mono mode telecommunication fiber to the wavelength as short as 200 nm. The results show that a light source in the UV spectral region 228 to 253 nm is most effective in photo inducing refractive index changes in such optical fibers. Therefore, we used a KrF excimer laser with wavelength ~248 nm as light source, and applied the phase mask technique to writing fiber grating. This method has the significant advantage for its much less relaxed requirement on the spatial coherence of exposure light source. The device (i-e grating) characteristics especially, in sensing application, were investigated. In addition, the possibility of using such device as a temperature and strain sensors is also discussed in detail.

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1. Introduction

With the rapid development in sensing and telecommunication, optical fibers play an important role in transmission systems as a low-loss and wide-bandwidth medium. However, traditional methods of processing the optical signals in such systems have been via interruption of the fiber and subsequent insertion of bulk- or integrated-optic components. For these methods of signal processing, there are several major disadvantages including high device insertion loss, high back reflection, fiber-to-device interfacing problem, and mechanical and thermal stability. Fiber Bragg grating (FBG) has been of great interest in communications such as tunable filter, in wavelength division multiplexing and demultiplexing (WDM/D), and as fiber sensors such as temperature sensor, vibration sensor, pressure sensor [1, 2, 3, 4] and strain sensitivity [5]. As a result, there has been a steady increase in the development of continuous-fiber components capable of performing a variety of essential functions, e.g., wavelength multiplexing and directional switching. The emergence of UV induced fiber gratings in germanium-doped silica fibers [6, 7] has generated significant interest for their numerous applications in optical fiber devices. Light-sensitive fibers offer exciting prospects for the development of such devices as fiber grating assisted semiconductor lasers [8], mode couplers [9], sensors [10], etc. However, it had been a difficult task to fabricate fiber gratings with UV laser sources for their low coherent length until 1993 when Hill et al. [11] proposed a convenient method based on the near-contact exposure through a phase mask. This method has the

significant advantage for its much less relaxed requirement on the spatial coherence of exposure light source.

In this paper, we report and demonstrate the importance of the coherence light source in the UV laser used write Bragg grating in a core of fiber optic with the phase mask technique. In addition, the use of such a device for temperature sensors and strain sensors is discussed. In accordance with the applied temperature and strain effect on an optical fiber Bragg grating this corresponds to change in the grating spacing which shifts in the Bragg wavelength. In this experiment can be using an application in the telecommunication and fiber optic sensors such as high temperature sensor, fire alarm sensor, vibration sensor, and pressure sensor.

2. Fabrication of fiber gratings

One of the most effective methods for inscribing Bragg gratings in photosensitive fiber is the phase masks technique. This method employs a diffractive optical element to spatially modulate the UV writing beam. Generally, phase masks may be formed either holographically or by electron beam lithography. One of the advantages of the electron beam lithography over the holographic technique is that complicated patterns can be written into the mask's structure such as quadratic chirps and patterns. The phase mask technique (electron beam lithography) for writing fiber gratings has the advantages over the traditional holographic method because of its simpler writing setup and more reproducible characteristics. Specifically, the utilization of phase mask relaxes the strict requirement on the coherence of a UV

light source. On the other hand, to photo induce an index change in the fiber core, light absorption must somehow occur. Alkins measured the absorption spectrum in a standard germanium doped monomode telecommunication fiber to the wavelength as short as 200 nm [12]. The results show that a light source in the UV spectral region 228 to 253 nm is most effective in photoinducing refractive index changes in such optical fibers. Therefore, we used an excimer laser with wavelength 248 nm as light source, and applied the phase mask technique for writing fiber gratings.

Fig. 1 shows that the UV radiation at normal incidence to the phase mask and diffracted radiation is split into $m = 0$ and ± 1 order.

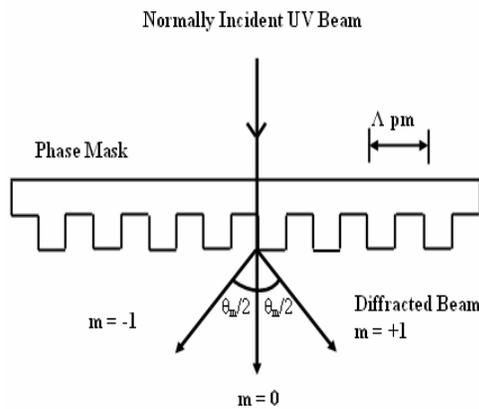


Fig. 1. Schematic of the UV radiation at normal incidence of a phase masks.

The interference pattern at the fiber of two beams of order ± 1 brought together has a period of the grating Λ_g related to the diffraction angle $\theta m/2$ by

$$\Lambda_g = \lambda_{uv} / 2 \sin (\theta m/2) = \Lambda_{pm} / 2 \quad (1)$$

where Λ_{pm} is the period of the phase mask, Λ_g is the period of the fringes and λ_{uv} is the UV wavelength. The period of the grating etched in the mask is determined by the required Bragg wavelength λ_B for the grating in the fiber, yielding

$$\Lambda_g = N \lambda_B / 2 n_{eff} = \Lambda_{pm} / 2 \quad (2)$$

where $N > 1$ is an integer indicating the grating period and n_{eff} is effective core index of fiber. The Bragg conditions are $\lambda_B = 2 n_{eff} \Lambda_g$.

The method employs a diffractive optical phase mask to spatially modulate the UV writing beam shown as Fig. 2, which may be formed holographically or by electron-beam lithography. The patterns can be written into the electron beams fabricated masks. The phase mask grating has a one-dimension surface-relief structure fabricated in high quality fused silica flat transparent to the UV writing beam. The profile of the periodic gratings is chosen such that when the UV beam is incident on the phase mask, the zero-order-diffracted beam is suppressed

to less than a 5% percent of the transmitted power. In addition, the diffracted plus and minus first orders are maximized, each containing, typically, more than 37% of the transmitted power. A near-field fringe pattern is produced by the interference of the plus and minus first-order diffracted beams. The period of the fringes is one half that of the mask. The interference pattern photoimprints a refractive index modulation i.e. Bragg grating in the core of the photosensitive fiber which is placed directly behind the phase masks [11]. A cylindrical lens is used to focus the fringe pattern along the fiber core. The phase mask greatly reduces the complexity of the fiber grating fabrication system. The simplicity of using only one optical element provides a robust and an inherently stable method for reproducing fiber Bragg grating. Since the fiber is usually placed directly behind the phase mask in the near field of the diffracting UV beams, sensitivity to mechanical vibrations and, therefore, stability problems are minimized. Low temporal coherence does not affect the writing capability due to the geometry of the problem.

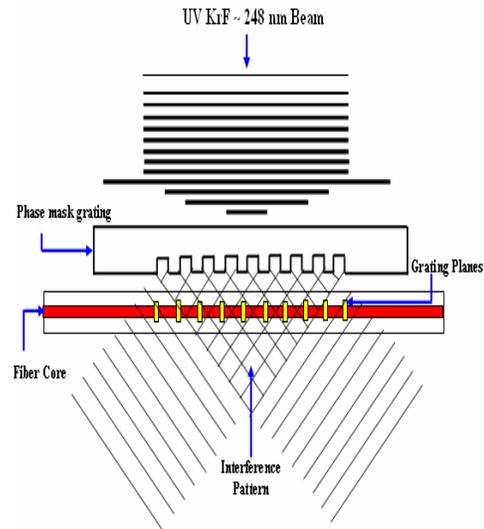


Fig. 2. The interference pattern photoimprints a refractive - index modulation in the core of a photosensitive optical fiber.

3. Fiber gratings sensing nature

As depicted previously, FBGs grating central wavelength λ_B is controllable in terms of the magnitude of average refractive index n_{eff} as well as gratings optical period Λ . However, these two factors have been proven to be ambient sensible. According to the literature, due to the photoelastic and thermal-optic natures, FBG fibers average refractive index and optical period are alterable upon in-fiber strain and ambient temperature [3]. Hence one may easily deduce that FBG fibers grating wavelength is tunable in terms of in-fiber strain and ambient temperature changes. In short, a strain and temperature sensor is achievable. Assuming an isothermal condition, FBGs

grating Bragg wavelength shift upon strain and temperature changes can be expressed as [3]

$$\Delta\lambda_B = 2(\Lambda \frac{\partial n}{\partial l} + n \frac{\partial \Lambda}{\partial l}) \Delta l + 2(\Lambda \frac{\partial n}{\partial T} + n \frac{\partial \Lambda}{\partial T}) \Delta T \quad (3)$$

where T is temperature and l is length of strain effect.

3.1. Strain sensitivity

According to equation (3), the first term represents the strain effect on an optical fiber. This corresponds to a change in the grating spacing and the strain optic induced change in the refractive index. The above strain effect term may be expressed as

$$\Delta\lambda_B = \lambda_B (1 - p_e) \epsilon_z \quad (4)$$

where p_e is an effective strain-optic constant defined as

$$p_e = n^2/2 [p_{12} - \nu (p_{11} + p_{12})] \quad (5)$$

where p_{11} and p_{12} are components of the strain optic tensor, n is the index of the core, and ν is the Poisson's ratio. For a typical optical fiber $p_{11} = 0.113$, $p_{12} = 0.252$, $\nu = 0.16$ and $n = 1.482$.

3.2. Temperature sensitivity

According to equation (3), the second term represents the temperature effect on an optical fiber. A shift in the Bragg wavelength due to thermal expansion changes the grating spacing and changes the index of refraction. This fractional Bragg wavelength shift for temperature change ΔT can be written as

$$\Delta\lambda_B = \lambda_B (\alpha - \zeta) \Delta T \quad (6)$$

where $\alpha = (1/\Lambda) (\partial\Lambda/\partial T)$ is the thermal expansion coefficient for the fiber ($\approx 0.55 \times 10^{-6}$ for silica). The quantity $\zeta = (1/n) (\partial n/\partial T)$ represents the thermo-optic coefficient and it is approximately equal to $8.6 \times 10^{-6} / ^\circ\text{C}$ for the germanium-doped silica core fiber.

4. Experiment

The experiment setup for inscribing Bragg grating with a phase mask is shown in Fig. 3. A KrF excimer laser was used as the UV source for inscribing Bragg grating with a phase mask. The loading of the mask and fiber was performed outside of the exposure unit, which was usually more convenient. The photosensitive fiber was positioned by removing the two round magnetic clamps and placing the fiber in the "V" –grooves on either side of the jig. Replacing the magnets clamps the fiber in place. The entire length of the fiber (from one end of the v-grooves to the other) should be stripped of its coating; otherwise the fiber was not sited properly at the correct separation. The photosensitive fiber was also attached to a mount that allowed its separation from the phase mask to be adjusted. Once the mask had been aligned in its holder, it did not need to be aligned again. Subsequent exposures can be made by simply changing the fibers in the v-grooves. The

aperture was inserted before the phase mask to limit the length of the grating to be written. The excimer laser (248 nm) was operated at 100 mJ with a repetition rate of 10 Hz to expose an 8 mm-long Bragg grating for duration of 90 min. The beam was directed into the phase mask and focused with a plane-cylindrical lens ($f = 200$ mm) onto the fiber. The dimension of the phase mask used in this experiment is $25 \text{ mm} \times 3 \text{ mm}$ and the period of phase mask grating corrugation is 1060.81 nm. The zero-order-diffracted beam was suppressed below 3% and each of the plus and minus first-order diffracted beams contained 37% of the transmitted light. Using this phase mask, Bragg gratings inscribed in fiber (single mode fiber type I having a diameter 125 μm effective core index ($n_{\text{eff}} = 1.447$ and fiber core is silica germanium boron). The duration of UV exposure was kept constant throughout the experiment. In this experiment, a broadband light source was launched into the fiber core traveled to the optical spectrum analyzer for a detected Bragg wavelength.

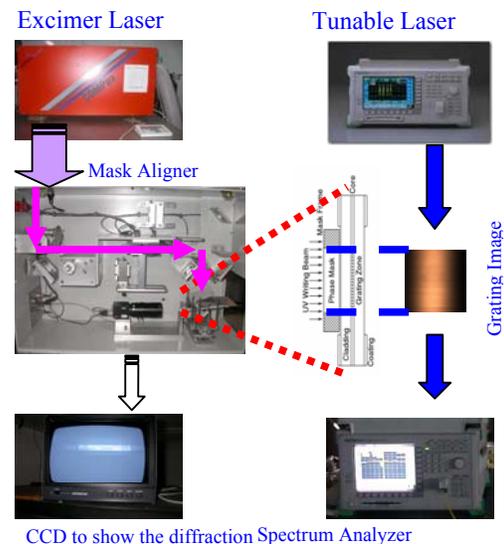


Fig. 3. The experiment setup for inscribing Bragg grating with a phase mask.

Experimental setup for strain sensitivity

The experimental setup for strain sensitivity of fiber Bragg grating system is shown in Fig. 4. Light from a broadband light source was launched into a fiber grating traveled to the detector and detected by the optical spectrum analyzer with Bragg wavelength. A 3 dB coupler was used to get the reflection spectra. As the fiber Bragg grating has two epoxies, one epoxy was inserted on the fixed stage and the other epoxy was inserted on the movable stage (micrometer) [13]. Using this setup, a physical elongation had been produced in a grating creating a tensile by varying the distance at the micrometer

(Movable stage) for micro strain ($\mu\epsilon$) from 0, 100 $\mu\epsilon$, 300 $\mu\epsilon$ to 1700 $\mu\epsilon$.

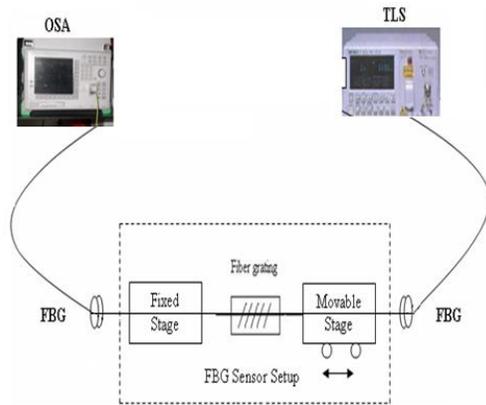


Fig. 4. The experiment setup used for strain sensitivity.

Experimental set up for temperature sensitivity

The experimental set up for temperature sensitivity of fiber Bragg grating system is shown in Fig. 5. Light from a broadband light source was launched into a fiber grating pass through via oven and traveled to be detected the Bragg wavelength (λ_B) by the optical spectrum analyzer. The fiber grating was placed inside the temperature controlled oven. The effect of temperature change from 25 °C, 45 °C to 185 °C on a fiber grating was observed by monitoring the Bragg wavelength shift on an optical spectrum analyzer.

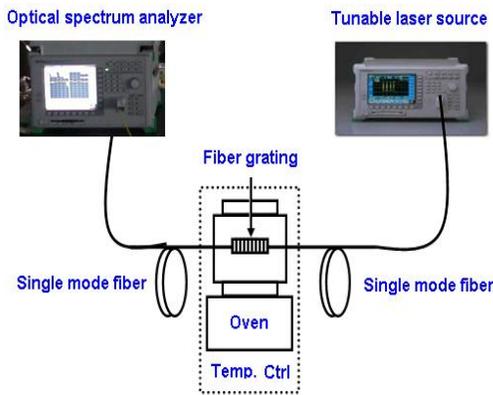


Fig. 5. The experiment setup used for temperature sensitivity.

5. Results and discussion

The results for inscribing Bragg grating with a phase mask technique are shown in Figs. 6 & 7. Perturbation of the grating results in a shift in the Bragg wavelength of the device which can be detected in either the reflected or transmitted spectra. The reflection method offers some advantages over the transmission method. In reflection only the light that matches the Bragg condition of the

grating is measured over relatively small background intensity. A 3-dB coupler was used to split off the reflection of the grating. The center wavelength of the grating reflection was measured by an optical spectrum analyzer. The reflectivity of fiber grating centered at Bragg wavelength 1534.991 nm was calculated by measuring the dip peak of the transmission spectrum as shown in Fig. 6 and the calculated reflectivity was about 79%.

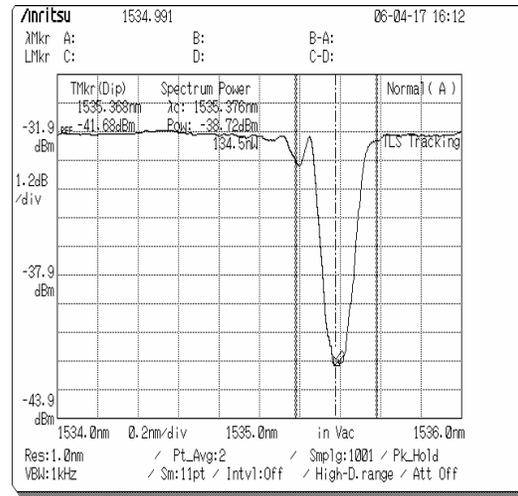


Fig. 6. Fiber Bragg grating transmission characteristics.

The bandwidth of the reflected signal depends on several parameters, particularly the grating length, but typically is ~ 0.1 to 0.4 nm in most sensor applications. The Bragg wavelength of this fiber grating was centered at 1534.991 nm, and its bandwidth measured at full width at half maximum (FWHM) was 0.32 nm.

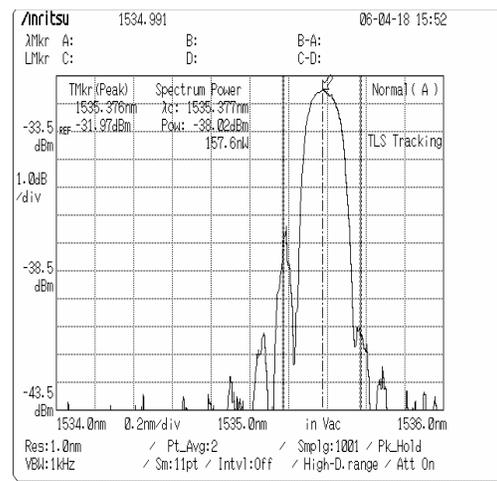


Fig. 7. Fiber Bragg grating reflection characteristics.

The effect of temperature and strain sensitivity of fiber Bragg grating is shown in Figs. 8 & 9. The primary

measurand influence of interest in the sensor community is the strain dependence of the Bragg wavelength. Fig. 8, shows the result under variable strain from 0 $\mu\epsilon$ to 1700 $\mu\epsilon$ at constant temperature 25 °C, have a shift in the Bragg grating wavelength as a function of applied strain for a 1534.991 nm grating. The measured strain response at a constant temperature is found to be:

$$(1/\lambda_B) d\lambda_B / d\epsilon = 0.78 \times 10^{-6} \mu\epsilon^{-1} \quad (7)$$

Wavelength-strain sensitivity Rule of thumb at $\lambda_B = 1550$ nm; <1.2 nm / 1000 $\mu\epsilon$ >.

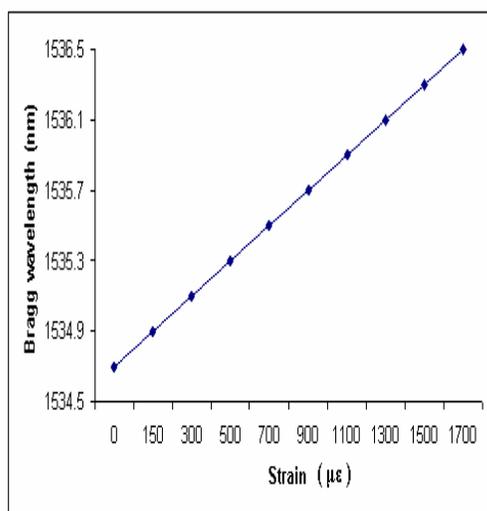


Fig. 8. Graph of Bragg wavelength as a function of applied strain.

Fig. 9, shows the effect of temperature for a fiber grating 1534.991 nm. The results under variable temperature from 25 °C to 185 °C at constant strain have a shift in the Bragg grating wavelength as a function of applied temperature for a 1534.991 nm grating. The dependence of the Bragg wavelength on temperature arises due to two primary effects: the dependence of the index of refraction of the glass on temperature and the thermal expansion of the glass. In silica fibers, the former of these is the dominant effect, accounting for $\sim 95\%$ of the observed shift. The measured temperature response at a constant strain is found to be:

$$(1/\lambda_B) d\lambda_B / dT = 6.67 \times 10^{-6} \text{ } ^\circ\text{C}^{-1} \quad (8)$$

Wavelength-temperature sensitivity Rule of thumb at $\lambda_B = 1550$ nm; <0.009 nm / $^\circ\text{C}$ >.

From these results it can be observed that the wavelength of Bragg grating increases with both temperature and strain. The good linear relationship between temperature and Bragg wavelength has shown the potential of using for a device sensing applications, railway track, bridge, building and earthquake monitoring,

the strain or temperature measurement can be used for the required monitor.

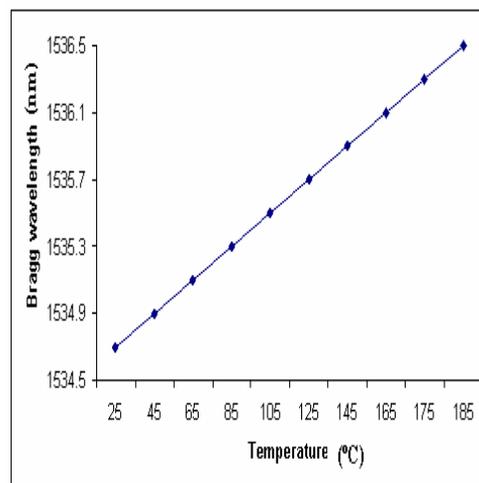


Fig. 9. Graph of Bragg wavelength as a function of temperature change.

6. Conclusions

The use of UV laser source for fiber Bragg grating by phase mask writing has been demonstrated. One of the techniques commonly used to inscribe Bragg grating in the core of optical fibers uses a phase mask to spatially modulate and diffract the UV beam to form an interference pattern. The interference pattern induces a refractive index modulation in the core of the photosensitive fiber, which is placed directly behind the phase mask. The phase mask technique is relatively easy to fabricate, and makes the core grating an ideal candidate for use in telecommunication and sensing applications such as temperature sensing and strain sensing. Results of transmission spectrum and reflectivity of light in fiber Bragg grating have been related with Bragg wavelength. When the results of the strain effect and applied temperature on an optical fiber Bragg grating are compared, this corresponds to a change in the grating spacing and the refractive index of the fiber. Therefore, it shifted in the Bragg wavelength. In this result, it can be used in applications, in the telecommunication and fiber optic sensors as high temperature sensor, fire alarm sensor, vibration sensor, and pressure sensor. The fiber grating for communication may be implemented in the system for signal filtering, gain flatness, optical memory etc., the other increase of the communication capacity and performance.

References

- [1] R. Kashyap, Fiber Bragg Grating, Academic Press, London (1999).
- [2] Y. Zhang, D. Feng, Z. Liu, Z. Guo, X. Dong, K. S. Chiang, C. B. Chu, IEEE Photonics Tech. Lett. **15** (6), 618 (2001).
- [3] A. Othonos, K. Kalli, Artech House, Inc. (1999).

- [4] K. T. V. Grattan, B. T. Meggitt, Kluwer Academic Publishers, London (2000).
- [5] O. Frazao, R. Romero, G. Rego, P. V. S. Marques, H. M. Salgado, J. L. Santos, *Electronics Lett.* **38**(14), 693 (2002).
- [6] K. O. Hill, Y. Fujii, D. C. Johnson, B. S. Kawasaki, *Appl. Phys. Lett.* **32**, 647 (1978).
- [7] G. Meltz, W. W. Morey, W. H. Glenn, *Opt. Lett.* **14**, 823 (1989).
- [8] D. M. Bird, J. R. Armitage, R. Kashyap, R. M. A. Fatah, K. H. Cameron, *Electron Lett.* **27**, 1115 (1991).
- [9] K.O. Hill, B. Malo, K. A. Vineberg, F. Bilodeau, D. C. Jonson, I. Skinner, *Electron. Lett.* **26**, 1270 (1990)
- [10] L. T. Blair, S. A. Cassidy, *Electron. Lett.* **28**, 1734 (1992).
- [11] K. O. Hill, B. Malo, F. Bilodeau, D. C. Jonson, J. Albert, *Appl. Phys. Lett.* **62**, 1035 (1993).
- [12] R. M. Alkin, *Opt. Lett.* **17**, 469 (1992).
- [13] B. A. Tahir, J. Ali, R. A. Rahman, *Am. J. of Appl. Sci.* (special issue), 40 (2005).

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