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Enhancement of InGaN/GaN Flip-Chip ITO LEDs with Incline Sidewalls Coated with TiO_2/SiO_2 Omnidirectional Reflector

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The light extraction enhancement of GaN-based flip-chip indium-tin oxide light-emitting diodes (FC ITO LEDs) with an inclined sidewall coated with TiO_2/SiO_2 omnidirectional reflectors (ODRs) is presented. At a driving current of 350 mA and a chip size of 1×1 mm, the light output power and the light extraction enhancement of the FC ITO LEDs coated TiO_2/SiO_2 ODRs with inclined sidewall reached 183 mW and 15% when compared with the results from the same device, FC ITO LEDs coated TiO_2/SiO_2 ODRs with vertical sidewall. Furthermore, by examining the radiation patterns of the FC ITO LEDs, the increased optical power within 150° cone contributed to the stronger enhancement around the vertical direction of an inclined sidewall ODR within blue regime. Our work offers promising potential for enhancing output powers of commercial light-emitting devices.
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GaN-based material is a direct wide bandgap semiconductor that has attracted considerable interest in applications for blue, green and ultraviolet light-emitting diodes (LEDs). The availability of higher brightness, high power and large area of GaN-based LEDs has enabled their applications in traffic signals, back-side lighting in liquid crystal display and backlight for various handheld devices.[1] Due to the large refractive index difference between GaN of 2.5 and air of 1.0, the total internal reflection is mainly responsible for the photon trapping. Emitting photons that strike the GaN-air interface at angles exceeding the critical angle θ_c are reflected back, the majority of which are guided laterally through the air-GaN-sapphire waveguide structure. Thus, the critical angle at which light generated in the InGaN–GaN active region can escape is approximately $[\theta_c = \sin^{-1}(n_{\text{air}}/n_{\text{GaN}})] \sim 23°$, which limits the external quantum efficiency of conventional GaN-based LEDs to only a few percent. However, there is a great need to improve the external quantum efficiency of GaN-based LEDs in order to further increase their light output power.

Several approaches have been proposed to improve the external quantum efficiency and the output power of packaged LEDs; light emitted downward toward the substrate must be reflected upward in order to contribute to usable light output[2-4] and the output light could be enhanced through the sample surface or the sidewall profile.[5-8] Chang et al. reported 10% output power enhancement from the InGaN–GaN multiple quantum well (MQW) LEDs by the introduction of the wavelike textured sidewalls.[5] Kao et al. reported the experiment results for enhancing light extraction efficiency from the GaN-based LEDs with ~23° undercut sidewalls.[6] Lin et al. reported the enhancement of light extraction efficiency using photoelectrochemical wet oxidation on the GaN-based LEDs with inclined undercut sidewalls.[8] All these methods have one thing in common, which is that photons generated within the LEDs experience multiple opportunities to find the escape cone. Bhat, Ludowise, and Steigerwald[9] proposed a dielectric distributed Bragg reflector (DBR) coated on the inclined mesa wall of a flip-chip LED to enhance the light output power. The dielectric DBR is selected to maximize the reflection of light to enhance light extraction of the flip-chip LED.

DBRs have many advantages, such as very low optical loss, high reflectance, and high mechanical robustness. A one-dimensional (1D) periodic dielectric structure possessing this characteristic is known as an omnidirectional one-dimensional photonic crystal (1D PhC). Total reflection of light with incidence angle onto a periodic structure can be realized with the existence of a complete photonic bandgap (CPBG) at the wavelengths of interest.[10] Since there is no allowed photon propagation state for wavelengths within the CPBG, an omnidirectional reflector (ODR) made from such 1D PhC can totally reflect the light with wavelengths within the CPBG at any incidence angle and polarization. Therefore, compared with a DBR mirror, a substantially higher reflectance can be achieved. In our previous work, we have demonstrated enhancement in the extracted light intensity for a GaN-based LED with p-side up and flip-chip configuration incorporated with an ODR composed of alternate layers of TiO_2 and SiO_2.[4,11] In this paper, we have designed and fabricated a flip-chip indium-tin oxide LED (FC ITO LED) coated TiO_2/SiO_2 ODR with inclined sidewalls.

Experimental

The schematic cross-sectional representations of the structures of InGaN/GaN vertical-injection LED coated ODRs we proposed are shown in Fig. 1a, with vertical sidewall, and Fig. 1b, with inclined sidewall. The GaN-based LED samples were grown by metallorganic chemical vapor deposition with a rotating-disk reactor (Emcore) on a *c*-axis sapphire (0001) substrate at the growth pressure of 200 mbar. The LED structure consists of a 50 nm thick GaN nucleation layer grown at 500°C, a 2 μm undoped GaN buffer, a 2 μm Si-doped GaN buffer layer grown at 1050°C, an unintentionally doped InGaN/GaN MQW active region grown at 770°C, a 50 nm thick Mg-doped p-AlGaN electron blocking layer grown at 1050°C, a 0.25 μm thick Mg-doped p-GaN contact layer grown at 1050°C and a Si-doped InGaN/GaN short period superlattice structure. The MQW active region consists of five periods of 3 nm/7 nm thick InGaN/GaN quantum well layers and barrier layers. After annealing to activate Mg in the p-type layers, the FC ITO LEDs coated TiO_2/SiO_2 ODR were fabricated using standard process with a mesa area of 1×1 mm, the same as in Ref. 4.

Figure 1a shows the schematic diagram of the FC ITO LED coated TiO_2/SiO_2 ODR with vertical sidewall. We partially etched the surfaces of the LED samples using Cl_2/Ar as the etching gas by inductive-coupled-plasma reactive ion etching (ICP-RIE) until the n-type GaN layers were exposed. A 300 nm thick ITO layer was subsequently evaporated onto the sample surface by electron beam (E-beam) evaporation for current spreading. The ITO layer had a high electrical conductivity (about $1.7 \times 10^1\ \Omega^{-1}\ \text{cm}^{-1}$) and a high transparency (>95% at 460 nm). Ti/Al/Ni/Au contacts were subsequently deposited onto the exposed n-type GaN layers to serve as the n-type electrodes. SiO_2 layers were then deposited over all wafers by plasma enhanced chemical vapor deposition. Photolithography and HF solution etching were subsequently performed to define

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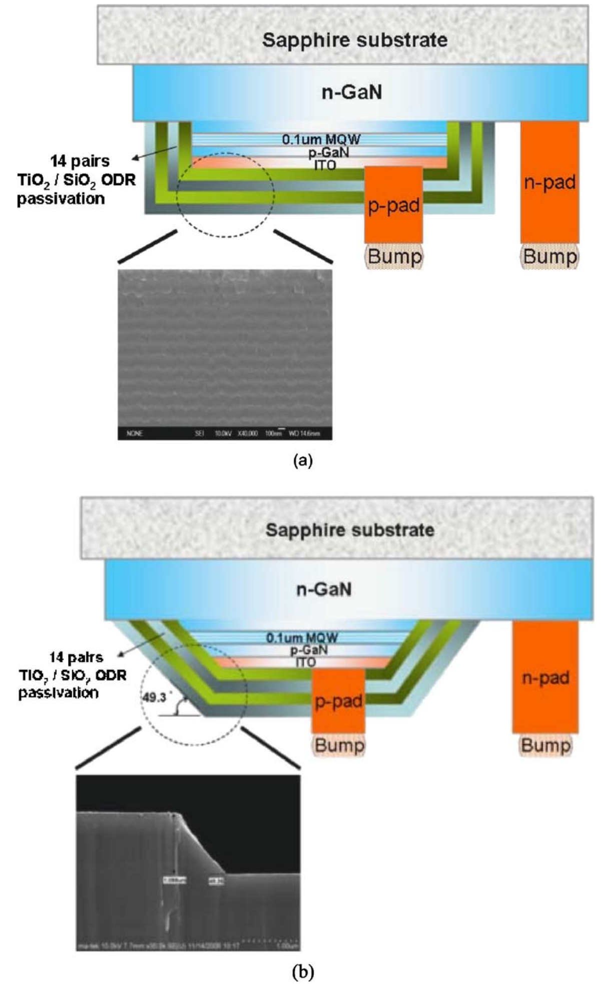


(a)

(b)

Figure 1. (Color online) Schematic diagram of the GaN-based FC ITO LEDs (a) containing the TiO_2/SiO_2 ODR, and (b) with ~50° inclined angle coated TiO_2/SiO_2 ODR. The inset shows the SEM picture of the ~50° inclined sidewall profile.

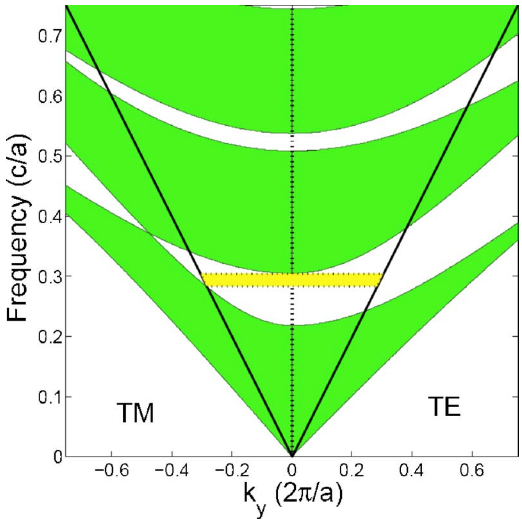


Figure 2. (Color online) Photonic band structure diagram of a 1D PC composed of TiO_2 and SiO_2 multilayers. Refractive indexes and layer thickness are assumed to be $n_1 = 2.52$, $d_1 = 56$ nm for TiO_2, and $n_2 = 1.48$, $d_2 = 77$ nm for SiO_2. The green and white regions distinguish between the allowed and forbidden photon states, respectively. The region with yellow area of the complete photonic bandgap (CPBG) represents an omnidirectional reflection region.

the P/N pad pattern for bump electroplating. The close-up scanning electron microscopy (SEM) image in Fig. 1a shows the step coverage of the SiO_2 films which was well controlled to cover the entire chips. Figure 1b depicts a schematic diagram of the FC ITO LED device coated TiO_2/SiO_2 ODR with an inclined sidewall. Instead of depositing TiO_2/SiO_2 ODR on the mesa structure directly, an additional etching process for FC ITO LEDs to form inclined sidewalls about 50° was carried out to mesa etching by using the ICP-RIE process. The inclined angle of the sidewall profile is defined as the angle between the horizontal line and sidewall. The inclined angle could be well controlled by using different ICP-RIE etching condition. The inset of Fig. 1b shows the SEM picture of inclined sidewalls profile of the FC ITO LED coated TiO_2/SiO_2 ODR with an inclined sidewall. It can be observed that the about 50° oblique inclined sidewall profile compared with initial etching mesa. $Au_{80}Sn_{20}$ solder was used for electrical and mechanical interconnection due to its very high reliability of good mechanical properties, good thermal conductivity, and low growth of intermetallic phase. Au_{80}/Sn_{20} (1600/400 nm) layers were then evaporated onto both FC ITO LED device coated TiO_2/SiO_2 ODR with vertical and inclined sidewall samples while P/N bumps were defined by the lift-off process. During the bonding process, chips were picked, orientated, and flipped by a die bonder system. The FC ITO LED was soldered onto an AlN submount. For comparison reasons, both FC ITO LED devices coated TiO_2/SiO_2 ODR with vertical and inclined sidewall were fabricated from exactly the same epitaxial wafer with the same chip size.

In this paper, the TiO_2/SiO_2 ODR structure is similar to Ref. 4. An ODR with 14 pairs of TiO_2/SiO_2 (as shown in inset of Fig. 1b for a SEM picture), was evaporated onto both samples by an E-beam evaporator at 150°C, and at an oxygen partial pressure of 2×10^{-4} Torr with Ar and O_2 as the ion source inlet gases. The film deposition rates of TiO_2 and SiO_2 were 0.4 and 0.8 nm/s, respectively. By the modal transmission-line method[12] to calculate the various thicknesses as shown in Fig. 2, we found the most optimal CPBG at frequencies between 0.282 c/a and 0.304 c/a, where c is the speed of light and a is the lattice constant. We chose the lattice constant $a = 133$ nm to give a CPBG centered at 465 nm. Thus we found that our TiO_2/SiO_2 ODR has a CPBG from 437 to 472 nm if the thickness of TiO_2 and SiO_2 layers were chosen as 56 and 77 nm, respectively. We observed that rather low transmission ($<0.05\%$) can be achieved from 441 to 465 nm from the angle dependent

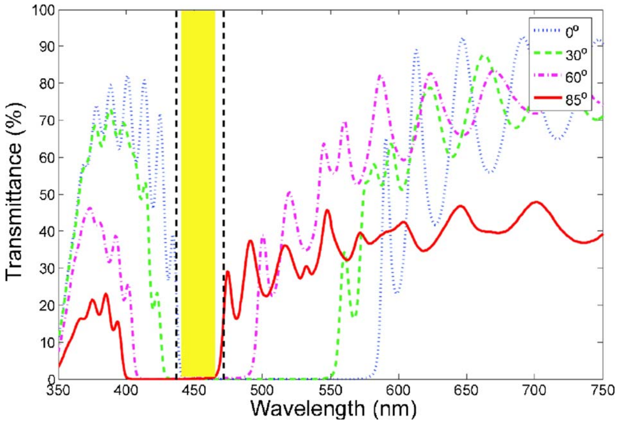


Figure 3. (Color online) Measurement transmittance results of the four transmittance curves with different incidence angles (e.g., 0°, 30°, 60°, 85°) for unpolarized light vs wavelength.

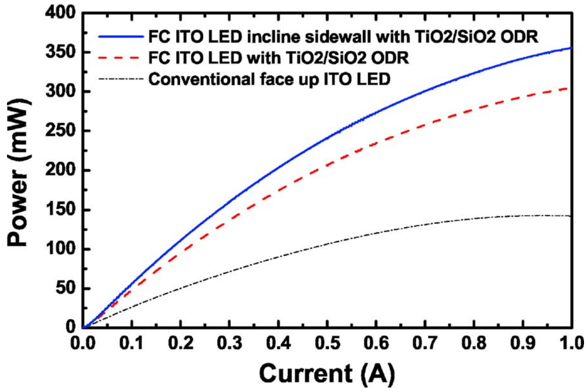


Figure 4. (Color online) EL intensity-current (*L-I*) characteristics of the FC ITO LEDs with an inclined sidewall coated TiO_2/SiO_2 ODR, FC ITO LEDs with TiO_2/SiO_2 ODR and conventional face up ITO LEDs, respectively.

transmission measurements. Figure 3 shows the measured transmittance at incidence angles of 0°, 30°, 60°, and 85° for unpolarized light as a function of the wavelength. We observed that rather high reflectance ($>99.5\%$) can be achieved from 441 to 465 nm, and up to an incidence angle of 85° (e.g., the yellow region). This wavelength region falls in the CPBG shown in Fig. 3 and is expected from the photonic band diagram in Fig. 2.

Results and Discussion

We performed electroluminescence measurements by injecting a continuous current into our LEDs at room temperature. The light output was detected by a calibrated integrating sphere with Si photodiode on the package device. We found that the measured forward voltages under injection current 350 mA at room temperature for the FC ITO LED device coated TiO_2/SiO_2 ODR with vertical and inclined sidewall and the conventional face up ITO LED were all about 3.4 V. It was also found that the *I-V* curves were almost identical for the FC ITO LED coated TiO_2/SiO_2 ODR with vertical and inclined sidewall.

The intensity-current (*L-I*) characteristics of the three different types of LEDs were shown in Fig. 4. We clearly observed that the light output power of the FC ITO LED coated TiO_2/SiO_2 ODR with the inclined sidewall was larger than that with vertical sidewall under all driving currents. At an injection current of 350 mA, we found that the MQW emission peaks of those three different devices were all located at about 465 nm, and the light output power of the FC ITO LED coated TiO_2/SiO_2 ODR with vertical and inclined sidewall and the conventional face up ITO LED were approximately 183, 158, and 83 mW, respectively. In other words, the FC ITO LED coated TiO_2/SiO_2 ODR with inclined and vertical sidewall show the light output power enhancement by 122% and 92%, respectively, when compared to the conventional face up ITO LED. The FC ITO LED coated TiO_2/SiO_2 ODR with an inclined sidewall increased the light output power by a factor of 1.15 more than the device with vertical sidewall. It indicated that the FC ITO LED coated TiO_2/SiO_2 ODR with about 50° inclined sidewall had better light extraction efficiency than that with vertical sidewall.

We also measured the light output radiation patterns of the FC ITO LED coated TiO_2/SiO_2 ODR with vertical and inclined sidewalls at a driving current of 350 mA, as shown in Fig. 5. We mounted both structures on the header only and without epoxy pack-

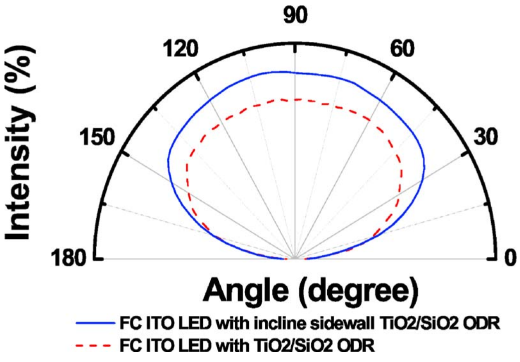
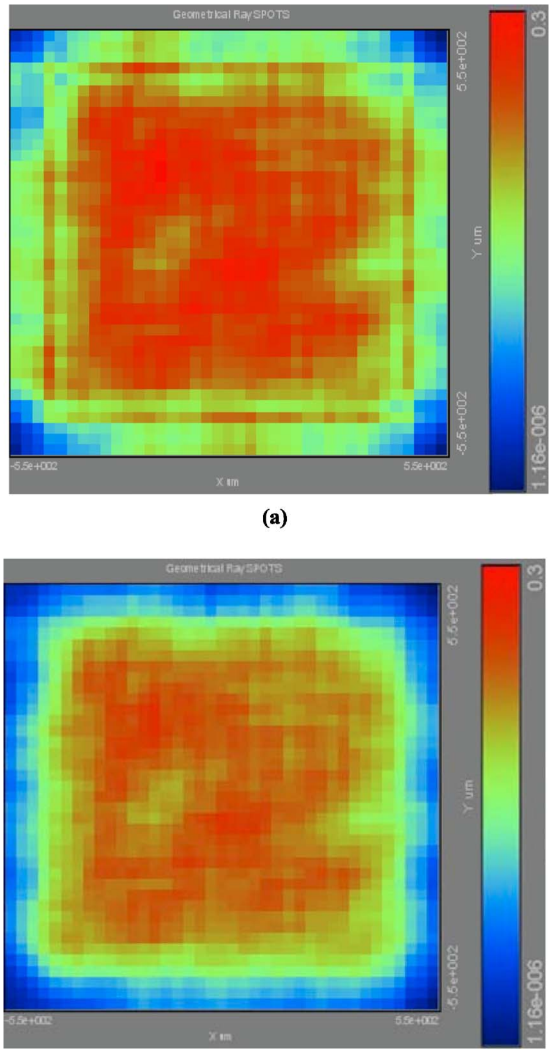


Figure 5. (Color online) Measurements of the far-field patterns distribution from the FC ITO LEDs with an inclined sidewall coated TiO_2/SiO_2 ODR and the FC ITO LEDs with TiO_2/SiO_2 ODR, respectively.

Table I. Parameters of structure layer in the simulated GaN-based FC ITO LEDs with TiO_2/SiO_2 ODR.

Layer	Sapphire	n-GaN	MQW	p-GaN	ITO	TiO_2	SiO_2
Thickness (μm)	100	2.0	0.1	0.25	0.2	0.056	0.077
Refractive index	1.63	2.5	2.3	2.5	2.0	2.52	1.48



(b)

Figure 6. (Color online) Top-view ray tracing images of the (a) FC ITO LED with an inclined sidewall coated ODR and (b) FC ITO LED with ODR.

age. Then the far-field pattern was measured from 0° to 180° by the conventional goniometric radiometer measurement technique. It can be seen that the FC ITO TiO_2/SiO_2 ODR LED with inclined sidewall shows higher extraction efficiency with a view angle about 150° than the LED with vertical sidewall. This enhancement is attributed to the higher reflectance of TiO_2/SiO_2 ODR coated on inclined sidewall within the blue regime when compared to TiO_2/SiO_2 ODR coated on vertical sidewall.

We also simulated the light propagation and reflection using the ray tracing method provided by Advanced System Analysis program software (ASAP). For simplicity, we employed a three-dimensional model on both GaN-based FC ITO TiO_2/SiO_2 ODR LED with vertical and with about 50° inclined sidewall. In addition, the simulation structure neglected sidewalls roughness and the absorption coefficient. The relative thickness and refractive index of each structure layer of the simulated GaN-based FC ITO TiO_2/SiO_2 ODR LEDs are described in Table I. The top mesa area of both FC ITO LEDs was 1×1 mm. Figures 6a and b show the top-view ray tracing images of FC ITO TiO_2/SiO_2 ODR LED with inclined and vertical sidewall, respectively. The x and y axes correspond to the chip length, 1×1 mm, and the color represents the light intensity. The result also shows the light extraction efficiency can be greatly enhanced by the inclined sidewall. Such an enhancement could have a larger probability to be scattered from the inclined sidewall and, thus, achieve high brighter LEDs.

Conclusion

In conclusion, GaN-based FC ITO TiO_2/SiO_2 ODR LEDs with an inclined sidewall were designed and fabricated. At a driving current of 350 mA and a chip size of 1×1 mm, the light output power and the light extraction enhancement of FC ITO TiO_2/SiO_2 ODR LEDs with an inclined sidewall reaches 183 mW and an enhancement of 30% when compared to the same device without the inclined sidewall. Furthermore, stronger enhancement around the vertical direction and wider view angle as shown in the radiation patterns of the FC ITO TiO_2/SiO_2 ODR LED with inclined sidewall showed stronger optical power within 150° cone due to the higher reflectance and the inclined sidewall of the designed ODR within blue regime. Our work offers promising potential for enhancing output powers of commercial light emitting devices.

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References

1. M. Koike, N. Shibata, H. Kato, and Y. Takahashi, *IEEE J. Sel. Top. Quantum Electron.*, **8**, 271 (2002).
2. J. K. Kim, Th. Gessmann, H. Luo, and E. F. Schubert, *Appl. Phys. Lett.*, **84**, 4508 (2004).
3. S. J. Chang, C. S. Chang, Y. K. Su, C. T. Lee, W. S. Chen, C. F. Shen, Y. P. Hsu, S. C. Shei, and H. M. Lo, *IEEE Trans. Adv. Packag.*, **28**, 273 (2005).
4. C. H. Lin, C. F. Lai, T. S. Ko, H. W. Huang, H. C. Kuo, Y. Y. Hung, K. M. Leung, C. C. Yu, R. J. Tsai, C. K. Lee, T. C. Lu, and S. C. Wang, *IEEE Photon. Technol. Lett.*, **18**, 2050 (2006).
5. C. S. Chang, S. J. Chang, Y. K. Su, C. T. Lee, Y. C. Lin, W. C. Lai, S. C. Shei, J. C. Ke, and H. M. Lo, *IEEE Photon. Technol. Lett.*, **16**, 750 (2004).
6. C. C. Kao, H. C. Kuo, H. W. Huang, J. T. Chu, Y. C. Peng, Y. L. Hsieh, C. Y. Luo, C. C. Yu, C. F. Lin, and S. C. Wang, *IEEE Photon. Technol. Lett.*, **17**, 19 (2005).
7. C. F. Lin, Z. J. Yang, J. H. Zheng, and J. J. Dai, *IEEE Photon. Technol. Lett.*, **17**, 2038 (2005).
8. C. F. Lin, Z. J. Yang, B. H. Chin, J. H. Zheng, J. J. Dai, B. C. Shieh, and C. C. Chang, *J. Electrochem. Soc.*, **153**, G1020 (2006).
9. J. C. Bhat, M. J. Ludowise, and D. A. Steigerwald, U.S. Pat. 6,891,197B2 (2005).
10. J. Q. Xi, M. Ojha, J. L. Plawsky, W. N. Gill, J. K. Kim, and E. F. Schubert, *Appl. Phys. Lett.*, **87**, 031111 (2005).
11. C. H. Lin, J. Y. Tsai, C. C. Kao, H. C. Kuo, C. C. Yu, J. R. Lo, and K. M. Leung, *Jpn. J. Appl. Phys., Part 1*, **45**, 1591 (2006).
12. C. H. Lin, K. M. Leung, and T. Tamir, *J. Opt. Soc. Am. A*, **19**, 2005 (2002).