AIP Applied Physics Letters

Experimental demonstration of a long-period grating based on the sampling theorem

Min-Suk Kwon, Young-Bo Cho, and Sang-Yung Shin

Citation: Appl. Phys. Lett. **88**, 211103 (2006); doi: 10.1063/1.2206093
View online: http://dx.doi.org/10.1063/1.2206093
View Table of Contents: http://apl.aip.org/resource/1/APPLAB/v88/i21
Published by the American Institute of Physics.

Experimental demonstration of a long-period grating based on the sampling theorem

Min-Suk Kwon,[a)] Young-Bo Cho, and Sang-Yung Shin
Department of Electrical Engineering and Computer Science, Korea Advanced Institute of Science and Technology, 373-1 Guseong-dong, Yuseong-gu, Daejeon 305-701, Korea

(Received 31 January 2006; accepted 3 April 2006; published online 22 May 2006)

We demonstrate experimentally the feasibility of a long-period grating whose index change pattern is in the form of sampling a raised-cosine function. We call such a grating a long-period grating based on the sampling theorem (LPGST). The LPGST is thermo-optically induced by an array of electrodes with individual widths. The array period is equal to the sampling period of 100 μm, and the period of the sampled function is 395 μm. A fabricated polymer long-period waveguide grating using the LPGST has a desired resonance band in its transmission spectrum, which is generated by the periodicity of the sampled function.
[DOI: 10.1063/1.2206093]

Long-period grating (LPG) is a periodic refractive index perturbation induced in a waveguide structure. It makes two copropagating modes in the waveguide structure coupled together if they satisfy the phase-matching condition.[1] Recently, LPGs have been actively used in long-period waveguide grating (LPWG) devices,[2–5] which are integrated-optical filters with core and several cladding modes such as optical fiber. The core mode of a LPWG is coupled to a cladding mode, and its transmission spectrum has a resonance band generated by the LPG. The LPGs of LPWGs are, on the one hand, induced permanently and not controllable. Hence, the characteristics of a resonance band cannot be tuned without an additional tuning mechanism such as heating the LPWG. On the other hand, thermo-optically induced LPGs (TOLPGs) have been used to tune dynamically the attenuation of a resonance band.[6–8] However, the LPWGs using the TOLPGs have the problem that the attenuation tuning causes an unwanted change in the center wavelength of a resonance band. The limited tunability of the existing LPWGs arises since the LPGs have the same permanent or temporary index change in every period.

It was claimed that a desired resonance band may be generated by a grating whose index change in each period is determined by sampling the index perturbation that generates the same resonance band.[9,10] Such a grating is called a LPG based on the sampling theorem (LPGST) in this letter. If each period of a LPGST is independently controlled by the thermo-optic or electro-optic effect, the LPGST can have dynamically the form of sampling an arbitrary index perturbation. Thus a LPWG using this LPGST may be arbitrarily tunable.[11] Before implementing the dynamically controllable LPGST, in this letter, we demonstrate experimentally that the concept of a LPGST is feasible. For that purpose, we fabricated and measured a polymer LPWG using a thermo-optically induced LPGST.

The investigated LPWG is schematically shown in Fig. 1. It has the same waveguide structure as the LPWGs using the TOLPGs.[6–8] Its core mode is confined to a channel, and its cladding modes are confined to a cladding sandwiched by upper and lower buffer layers. On the surface of the upper buffer, electrodes used as heaters are placed at an interval of a sampling period Λ_S. Each electrode has its own width w_m. The electrodes are connected to each other by pads such that the same current flows through all the electrodes.

The index perturbation $\Delta n(x,z)$, i.e., the LPGST induced thermo-optically by the electrodes is expressed by

$$\Delta n(x,z) = \sum_{m=0}^{N-1} \Delta n_M(w_m) P(x, z - m\Lambda_S; w_m), \tag{1}$$

where $\Delta n_M(w)$ is the maximum index change induced by an electrode with a width w. The number of the electrodes is N. $P(x,z;w)$ denotes an index change distribution induced by an electrode which is centered at $z=0$ and has a width w. It is normalized such that $P(0,0;w)=1$. Since the electrodes are much longer than the width of the channel, the LPGST is assumed to be independent of y.

From the previously derived expression for an index change induced thermo-optically by an electrode,[6] $\Delta n_M(w)$ can be written as the product of a w-independent term Δn_0 and a w-dependent function $g(w)$. Δn_0 is the maximum index change induced by an electrode with a width $w_{\min}$, and $g(w_{\min})=1$. Since $\Delta n_M(w)$ decreases as the resistance of an

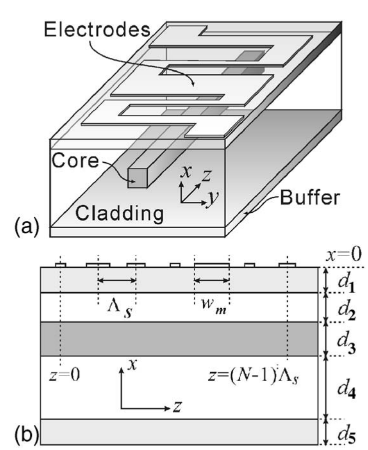

FIG. 1. Schematic diagram of the LPWG using the thermo-optic-induced LPGST. (a) Three-dimensional structure. (b) Layer structure.

[a)]Electronic mail: minsukkw@usc.edu

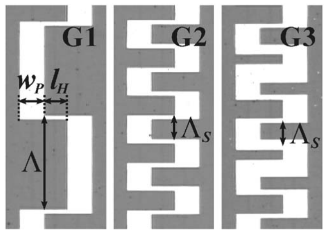

FIG. 2. Microscope images of the three sets of electrodes used as heaters for the LPWGs.

electrode decreases, it decreases with increasing w. Hence, $g(w)\leqslant 1$ if $w \geqslant w_{\min}$. The value of w_m is determined such that

$$\Delta n_M(w_m) = \Delta n_0 g(w_m) = \Delta n_0 \tfrac{1}{2}[\cos(2\pi m \Lambda_S/\Lambda) + 1]. \quad (2)$$

A raised-cosine function rather than just a cosine function is sampled since a thermo-optic index change in a polymer is always negative. According to the sampling theorem, all the information of the raised-cosine function is contained in the LPGST in Eq. (1) if $\Lambda_S \leqslant \frac{1}{2}\Lambda$. Hence, the LPGST may make the core mode and some cladding mode satisfy the phase-matching condition $\beta_0 - \beta_1 = 2\pi/\Lambda$,[1] where β_0 and β_1 are the propagation constants of the core and cladding modes, respectively.

The LPWG was made of the same thermocurable polymers as those used for the previous LPWGs using the TOLPGs.[7,8] Conventional processes such as spin coating, thermal curing, thermal evaporation of metal, photolithography, reactive-ion etching (RIE), and cleaving were used to fabricate it.[7] The dimensions of the fabricated LPWG are as follows. The buffer thicknesses d_1 and d_5 and the cladding thicknesses d_2 and d_4 in Fig. 1 are 2.6, 2.7, 8.7, and 9.5 μm, respectively. The core thickness d_3 is 5.2 μm and the core width is 5.5 μm. Because of the limitation of our RIE equipment, the core layer was etched to the depth of 4.5 μm, and so a rib waveguide was made.

To confirm the validity of the LPGST concept, the three LPWGs with different sets of electrodes were fabricated on the same substrate. Figure 2 shows the microscope images of the three sets of electrodes. The electrodes were made of approximately 100-nm-thick gold layer. The three sets in Fig. 2 are denoted by G1, G2, and G3, respectively. For G1, $\Lambda = \Lambda_S = 395$ μm and $N=52$. For G2, $\Lambda = \Lambda_S = 100$ μm and $N=200$. Thus all the electrodes of G1 and G2 have the same width $w_{\min}$, which was chosen to be 15 μm in this work. Actually, G1 and G2 induce the TOLPGs. Only G3 induces the LPGST. For G3, $\Lambda = 395$ μm, $\Lambda_S = 100$ μm, and $N=200$. If $g(w_m)$ approaches zero in Eq. (2), w_m increases infinitely. In a real device, w_m should be limited to some value such that the electrode cannot touch the adjacent electrodes. In this work, the maximum value of w_m was chosen to be 90 μm. In all the sets, the electrode length l_H and the pad width w_P are 100 and 100 μm, respectively.

Using a broadband source and an optical spectrum analyzer, we measured the transmission spectra of the fabricated LPWGs for each polarization. We observed a change in the transmission spectrum of every LPWG as we adjusted the power applied to each set of electrodes. The characteristics of the LPWGs measured for TE polarization are shown in Fig. 3. Figure 3(a) shows the transmission spectra of the LPWGs with G1, G2, and G3, respectively. They were obtained by applying the electrical powers of 655, 983, and 708 mW, respectively. Those power values maximized the attenuation of the major resonance bands in the transmission spectra of the LPWGs with G1 and G3, respectively. However, no apparent resonance band was observed in the case of the LPWG with G2, although the power was raised up to 983 mW. The minor sidebands in the transmission spectrum may arise from the coupling of the core mode to other cladding modes whose shapes in the x direction are the same as that of the cladding mode related to the major band. In addition, a little loss exists outside the resonance bands since the confinement of the core mode may be deteriorated due to a large thermo-optic index change, which is not uniform in the x direction.[7] Figures 3(b) and 3(c) show the center wavelengths and maximum attenuation of the major resonance bands due to G1 and G3 as functions of the applied power. As shown in the previous LPWGs using the TOLPGs, the center wavelength of the resonance band due to G1 is blue-shifted, and its maximum attenuation increases as the applied

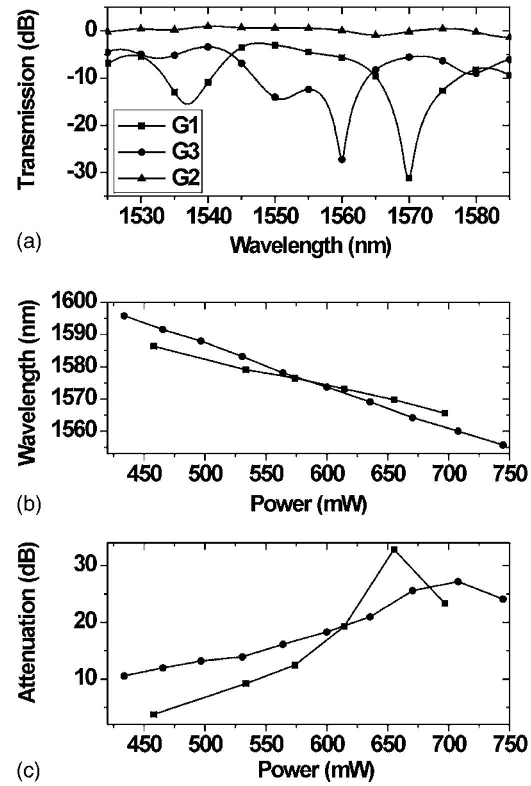

FIG. 3. Measured characteristics of the LPWGs for TE polarization. (a) Transmission spectra of the LPWGs with G1, G2, and G3. (b) The center wavelengths and (c) maximum attenuation of the major resonance bands due to G1 and G3 are given as functions of the applied power.

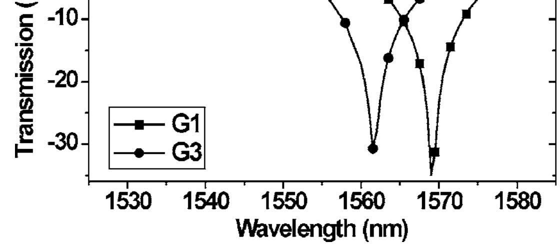

FIG. 4. Calculated transmission spectra of the LPWGs with G1 and G3 for TE polarization.

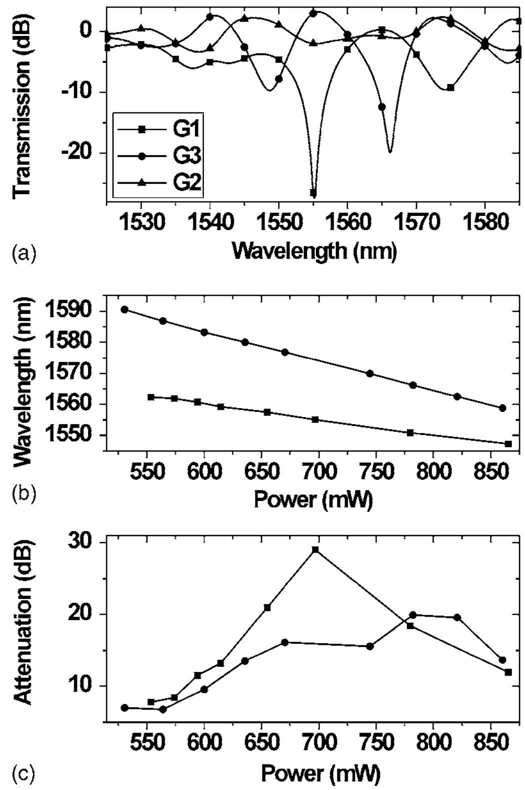

FIG. 5. Measured characteristics of the LPWGs for TM polarization. (a) Transmission spectra of the LPWGs with G1, G2, and G3. (b) The center wavelengths and (c) maximum attenuation of the major resonance bands due to G1 and G3 are given as functions of the applied power.

power increases. It decreases with the power larger than 655 mW due to the characteristics of codirectional coupling. The resonance band due to G3 has the characteristics similar to those of the resonance band due to G1. The differences between the characteristics of the resonance bands due to G1 and G3 exist since the index change distribution induced by G1, i.e., the TOLPG in the z direction, does not coincide exactly with the raised-cosine function determining the LPGST induced by G3. The results in Fig. 3 show that the LPGST induced by G3 generates the resonance band, which results not from the periodicity of the electrodes with the period Λ_S but from that of the sampled raised-cosine function with the period Λ.

To confirm the experimental results, the transmission spectra of the LPWGs with G1 and G3 were theoretically calculated by using the analysis method described previously.[6] The analysis method approximated the core layer including the channel and having a thickness of d_3 to a uniform layer with an effective index. For the approximated multilayer planar waveguide with the TOLPG or the LPGST, the coupled-mode equations were solved by integrating them numerically. Figure 4 shows the calculated transmission spectra. They agree relatively well with those in Fig. 3(a). In the calculation, the maximum index changes Δn_0 in Eq. (2) were 0.0032 and 0.0038 for the LPWGs with G1 and G3, respectively. The slightly larger value of Δn_0 for the LPWG with G3 also agrees well with the slightly larger power applied to G3 to get the transmission spectrum in Fig. 3(a).

Figure 5 shows the characteristics of the LPWGs measured for TM polarization. With the applied powers of 697 and 782 mW, G1 and G3, respectively, generated the resonance bands with maximum attenuation, which are shown in Fig. 5(a). The transmission spectrum of the LPWG with G2 in this figure was obtained by applying the power of 983 mW. Although the power was raised up to 983 mW, G2 did not generate any clear resonance band as in the case of TE polarization. In the spectrum, the transmission in some wavelength regions is larger than 0 dB. One possible reason is that cladding modes as well as the core mode are excited when light is launched to the input facet of the LPWG. In such wavelength regions, the excited cladding modes are coupled to the core mode such that the core mode seems to have a gain. Like Figs. 3(b) and 3(c), Figs. 5(b) and 5(c) show the relations of the characteristics of the resonance bands due to G1 and G3 to the applied power. Because of the dependence of the characteristics on polarization, those of TM polarization in Fig. 5 are somewhat different from those of TE polarization in Fig. 3. The dependence arises from fabrication-induced and heating-induced birefringence.[7]

In summary, we have fabricated and investigated the polymer LPWG using the thermo-optically induced LPGST. We have compared its characteristics with those of the LPWGs using the TOLPGs. The experimental results have demonstrated that the concept of a LPGST works. In the implemented device, each electrode for the LPGST cannot function independently since all the electrodes are connected. With the individual electrodes separated and manipulated independently by an electronic control module, the dynamically controllable LPGST mentioned above may be obtained. A LPWG using such a LPGST may have a dynamically controllable transmission spectrum, and will be useful in a dynamically reconfigurable optical system.

This work was partially supported by Novera Optics, Inc.

[1]T. Erdogan, J. Lightwave Technol. **15**, 1277 (1997).
[2]C. Martinez, B. Hoarau, L. Chirossel, O. Jacquin, and C. Guidoux, Opt. Commun. **233**, 97 (2004).
[3]H. Y. Tang, W. H. Wong, and E. Y. B. Pun, Appl. Phys. B: Lasers Opt. **79**, 95 (2004).
[4]Q. Liu, K. S. Chiang, K. P. Lor, and C. K. Chow, Appl. Phys. Lett. **86**, 241115 (2005).
[5]Q. Liu, K. S. Chiang, and K. P. Lor, IEEE Photonics Technol. Lett. **17**, 2340 (2005).
[6]M.-S. Kwon and S.-Y. Shin, J. Lightwave Technol. **22**, 1968 (2004).
[7]M.-S. Kwon and S.-Y. Shin, IEEE J. Sel. Top. Quantum Electron. **11**, 190 (2005).
[8]M.-S. Kwon and S.-Y. Shin, IEEE Photonics Technol. Lett. **17**, 792 (2005).
[9]H.-P. Nolting and M. Gravert, Opt. Quantum Electron. **27**, 887 (1995).
[10]H.-P. Nolting and M. Gravert, IEEE Photonics Technol. Lett. **7**, 315 (1995).
[11]M.-S. Kwon and S.-Y. Shin, Opt. Commun. (to be published); doi: 10.1016/j.optcom.2006.02.002.