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RESEARCH ARTICLE

Complex long-period-grating-assisted-coupler and its application in optical signal buffer

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Abstract By introducing gain/loss perturbation into periodic refractive index modulation, the unified coupled-mode equations and their close-form analytical solutions of complex long-period-grating-assisted-coupler (LPGAC) are deduced. Characteristics of power coupling are investigated and results show that unidirectional nonreciprocal signal transferring can be achieved by matching gain/loss with the refractive index modulation. Utilizing the feature of complex LPGAC, a novel optical signal buffer is proposed and its structure is examined in detail.

Keywords optical device, long-period-grating-assisted-coupler, optical signal buffer, complex-modulated-grating

1 Introduction

Compact optical devices are important for dense-wavelength-division-multiplexing optical communications system and optical networks like fiber-to-the-building or fiber-to-the-home in the future [1]. Grating-assisted-couplers, which combine the multi-ports characteristic of directional coupler with the wavelength selectivity of grating, have attracted considerable attention in recent years [2]. Compared with short-period (Bragg)-grating, long-period-grating-assisted-coupler (LPGAC) has several advantages such as easy-fabrication, wide tuning range and much lower insertion loss [3]. By far, most researches of LPGAC have only focused on periodic refractive index modulation. But long-period-grating (LPG) is an optical component that can be used to couple core mode with co-directional propagating cladding mode, whose field distributions are evanescent, which makes it possible for LPG to experience loss or gain induced by external adjust, such as the change of carrier concentration in semiconductor waveguides or pump conditions in rare-earth-doped waveguides [4–6]. In order to comprehensively understand the performance of LPGAC, complex-modulated-grating combined refractive index (real) with loss/gain (imaginary) modulation should be considered. In this paper, by directly deriving from full-scalar wave equations, unified coupled-mode equations and their close-form analytical solutions of the complex LPGAC are obtained. Power coupling characteristics of the complex LPGAC are analyzed and its application in optical signal buffer is discussed in detail.

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2 Theoretical model

Figure 1 shows the structure of complex LPGAC, which consists of two parallel but unequal waveguides in close proximity to each other. Because power transferring between asynchronous waveguides is not efficient, a grating is inscribed to facilitate power coupling by reducing the difference of propagation constants between two co-directional modes [7].

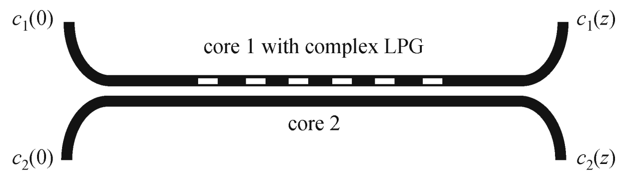

Fig. 1 Complex long-period-grating-assisted-coupler

Complex LPG is defined as a periodic longitudinal refractive index modulation (real part) combined with some gain or loss perturbation (imaginary part):

$$\Delta n = \Delta n_r \cos\left(\frac{2\pi}{\Lambda}z\right) - \mathrm{i}\Delta n_i \cos\left(\frac{2\pi}{\Lambda}z + \Delta\varphi\right), \qquad (1)$$

where Λ is the grating period. Δn_r and Δn_i are refractive index and gain ($\Delta n_i > 0$) or loss ($\Delta n_i < 0$) modulation, respectively. $\Delta\varphi$ represents the additional phase difference between the real and the imaginary part.

Based on weak coupling approximation, electric field $E(x,y,z,t)$ can be described as a linear combination of mode fields in isolation [8]:

$$E(x,y,z,t) = [c_1(z)\exp(-\mathrm{i}\beta_1 z)]\cdot\psi_1(x,y)\exp(-\mathrm{i}\omega t) + [c_2(z)\exp(-\mathrm{i}\beta_2 z)]\cdot\psi_2(x,y)\exp(-\mathrm{i}\omega t), \quad (2)$$

where $c_1(z)$, $c_2(z)$ are slowly varying mode amplitudes, $\psi_1(x,y)$, $\psi_2(x,y)$ are transverse field distributions and β_1, β_2 are propagation constants.

Inserting the complex perturbation (1) and electric field (2) into full-scalar wave equations:

$$[\nabla_t^2 + k^2 n^2(x,y)]E(x,y,z,t) = \mu\frac{\partial^2}{\partial t^2}[P(x,y,z,t)], \quad (3)$$

$$P(x,y,z,t) = \varepsilon_0 \Delta n^2 E(x,y,z,t) = 2\varepsilon_0 n\left[\Delta n_r \cos\left(\frac{2\pi}{\Lambda}z\right) - \mathrm{i}\Delta n_i \cos\left(\frac{2\pi}{\Lambda}z + \Delta\varphi\right)\right] \times E(x,y,z,t). \quad (4)$$

Then, multiply Eq. (3) by ψ_1 and integrate over infinite cross section, the evolution of the mode amplitudes can be expressed as the following unified coupled-mode equations:

$$\frac{\mathrm{d}c_1}{\mathrm{d}z} = -\mathrm{i}\left[K_{21}^r \cos\left(\frac{2\pi}{\Lambda}z\right) - \mathrm{i}K_{21}^i \cos\left(\frac{2\pi}{\Lambda}z + \Delta\varphi\right)\right] \times c_2 \exp[-\mathrm{i}(\beta_2 - \beta_1)z], \quad (5)$$

$$\frac{\mathrm{d}c_2}{\mathrm{d}z} = -\mathrm{i}\left[K_{12}^r \cos\left(\frac{2\pi}{\Lambda}z\right) - \mathrm{i}K_{12}^i \cos\left(\frac{2\pi}{\Lambda}z + \Delta\varphi\right)\right] \times c_1 \exp[-\mathrm{i}(\beta_1 - \beta_2)z], \quad (6)$$

where K_{vu}^r and K_{vu}^i ($v,u = 1,2$) are defined as

$$K_{vu}^r = \frac{\omega}{4}\oiint_\infty \left[2\varepsilon_0 n \Delta n_r \cos\left(\frac{2\pi}{\Lambda}z\right)\right]\cdot E_v E_u^* \mathrm{d}S = 2k_n \cos\left(\frac{2\pi}{\Lambda}z\right), \quad (7)$$

$$K_{vu}^i = \frac{\omega}{4}\oiint_\infty \left[2\varepsilon_0 n \Delta n_i \cos\left(\frac{2\pi}{\Lambda}z + \Delta\varphi\right)\right]\cdot E_v E_u^* \mathrm{d}S = 2k_\alpha \cos\left(\frac{2\pi}{\Lambda}z + \Delta\varphi\right), \quad (8)$$

where k_n and k_α are the real and imaginary coupling coefficients corresponding to the refractive index modulation or gain/loss perturbation, respectively.

Taking the second differential c_1'' of Eq. (5) and eliminating c_2, c_2' according to Eq. (6):

$$\frac{\mathrm{d}^2 c_1}{\mathrm{d}z^2} + \mathrm{i}2\delta\frac{\mathrm{d}c_1}{\mathrm{d}z} + \left\{k_n - k_\alpha \exp\left[\mathrm{i}\left(\frac{\pi}{2} - \Delta\varphi\right)\right]\right\} \cdot \left\{k_n + k_\alpha \exp\left[\mathrm{i}\left(\Delta\varphi - \frac{\pi}{2}\right)\right]\right\} = 0. \quad (9)$$

Thus, close-form analytical solution of the coupled-mode equations can be obtained in the matrix form as following:

$$\begin{bmatrix} c_1(z) \\ c_2(z) \end{bmatrix} = \begin{bmatrix} \left(\cos(\gamma z) + \mathrm{i}\frac{\delta}{\gamma}\sin(\gamma z)\right)\exp(-\mathrm{i}\delta z) & -\mathrm{i}\left(\frac{k_n - k_\alpha \exp[\mathrm{i}(\pi/2 - \Delta\varphi)]}{\gamma}\sin(\gamma z)\right)\exp(-\mathrm{i}\delta z) \\ -\mathrm{i}\left(\frac{k_n + k_\alpha \exp[\mathrm{i}(\Delta\varphi - \pi/2)]}{\gamma}\sin(\gamma z)\right)\exp(\mathrm{i}\delta z) & \left(\cos(\gamma z) - \mathrm{i}\frac{\delta}{\gamma}\sin(\gamma z)\right)\exp(\mathrm{i}\delta z) \end{bmatrix} \begin{bmatrix} c_1(0) \\ c_2(0) \end{bmatrix}. \quad (10)$$

Here, $\gamma = \sqrt{\delta^2 + k_n^2 - k_\alpha^2}$ with $\delta = \pi/\Lambda - (\beta_1 - \beta_2)/2$.

3 Analyses and discussion

First, we assume the phase difference $\Delta\varphi$ is $\pi/2$ and the signal is initially injected into core 1 ($c_1(0) = 1$, $c_2(0) = 0$) (as shown in Fig. 1). In order to investigate the influences of gain/loss perturbation on the power coupling characteristic, variations of normalized power $|c_1(z)|^2$ and $|c_2(z)|^2$ with the propagation distance for different relative modulation ratio k_α/k_n are calculated and results are depicted in Fig. 2. When both $k_\alpha = 0$ and $k_n = 0$, which corresponding to mismatched coupler itself, the power coupling efficiency will be too low to be useful, as shown in Fig. 2(a). This is because the propagation constants between the two waveguides are asynchronous and mismatched, which restrain the coupling process. By introducing the periodic refractive index grating, conventional LPGAC ($k_\alpha = 0$ but $k_n \neq 0$) will exhibit complete reciprocal and symmetric power exchange, as can be seen from Fig. 2(b). The initial power injected into one waveguide can be transferred totally to another waveguide by choosing suitable coupling length.

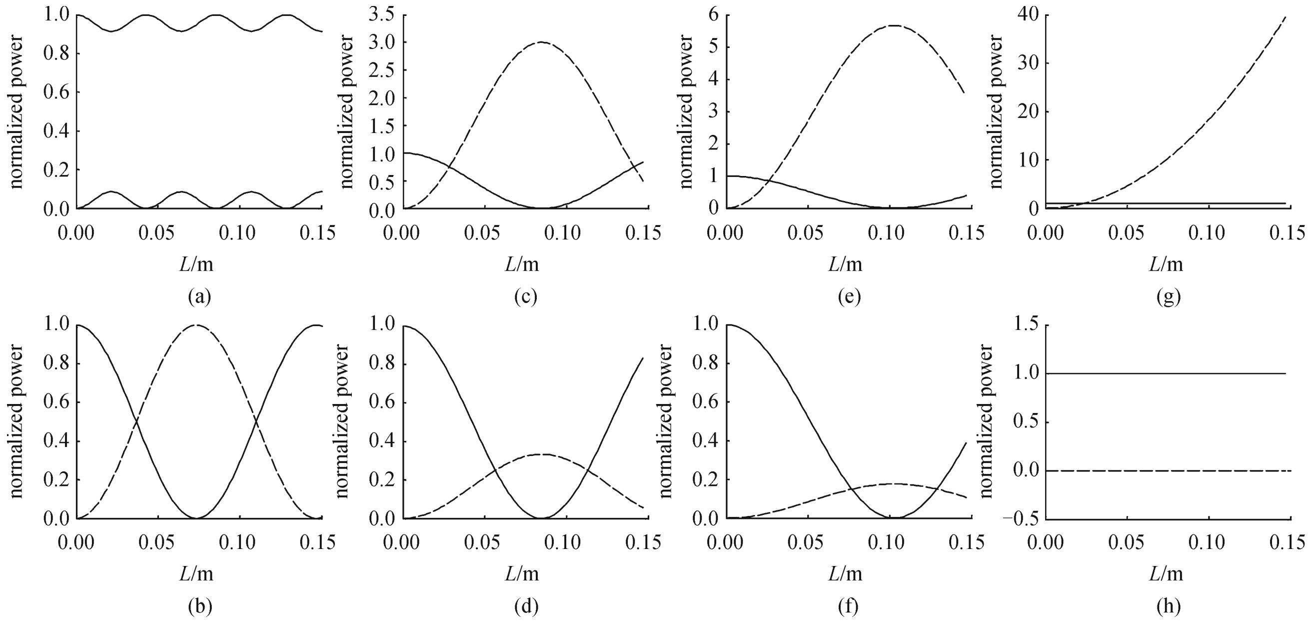

Fig. 2 Influence of gain/loss perturbation on power coupling characteristic (solid line: $|c_1(z)|^2$, dotted line: $|c_2(z)|^2$). (a) $k_n = 0$, $k_\alpha = 0$; (b) $k_n \neq 0$, $k_\alpha = 0$; (c) $k_\alpha/k_n = 0.5$; (d) $k_\alpha/k_n = -0.5$; (e) $k_\alpha/k_n = 0.7$; (f) $k_\alpha/k_n = -0.7$; (g) $k_\alpha/k_n = 1$; (h) $k_\alpha/k_n = -1$

If both refractive index modulation and gain/loss perturbation ($k_n \neq 0$ and $k_\alpha \neq 0$) are included, power coupling characteristic of the complex LPGAC is different from the conventional grating-assisted-coupler. As shown in Figs. 2(c)–2(f), although the two waveguides still be coupled alternately and periodically, the symmetry of power transferring can be broken by controlling gain/loss perturbation. Depending on how the perturbation (loss or gain) is induced, the maximum power coupled to cross waveguide is different and coupling length is kept increasing with relative modulation ratio $|k_\alpha/k_n|$. Especially, in the case of $k_\alpha/k_n = \pm 1$, the coupling length is extended to infinity, which means the coupling process is nonperiodical and nonreciprocal. When $k_\alpha/k_n = -1$ (as shown in Fig. 2(h)), both waveguides will remain their initial injected power due to the effect of refractive index modulation eliminated totally by the loss perturbation. However, when gain perturbation is introduced and matched with refractive index modulation ($k_\alpha/k_n = 1$), the coupled power will grow quadratically with the propagation distance. Simultaneously, the signal in the injected waveguide is unaffected (Fig. 2(g)).

However, if the signal is initially injected from another core 2, the power coupling behavior will be different from above. When loss perturbation is introduced ($k_\alpha/k_n = -1$), the signal can be transferred from core 2 to core 1. But, in the case of gain perturbation ($k_\alpha/k_n = 1$), power of the two waveguides are no longer intercoupled, as can be found from Eq. (10). Therefore, the complex LPGAC also demonstrates different coupling characteristic according to different input conditions.

4 Application

Because gain or loss can be interconverted and controlled accurately by external adjusting, such as applying additional stress in the coupler, or injected carrier concentration or optical pumping conditions in rare-earth-doped cores [7], many new optical devices can be exploited based on the nonreciprocal unidirectional coupling characteristic of the complex LPGAC.

By connecting the output port with the input port of waveguide 2, a novel optical signal buffer based on the complex LPGAC and a self-closed loop are proposed. Schematic diagram of the optical buffer is shown in Fig. 3. The grating period is chosen to make the wavelength of 1.55 μm satisfy the phase-matching condition. And the grating strength is $k_n L_g = \pi/2$ so as to provide complete signals coupling when the pump is turned off. Length of the self-closed loop is chosen to make the group delay of one roundtrip be much longer than the input signals.

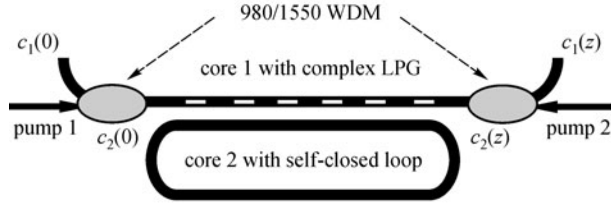

Fig. 3 Schematic diagram of optical signal buffer based on complex LPGAC and self-closed loop

Working principle of the optical buffer is described as follows. We assume three Gaussian pulse signals with spectral width much smaller than spectral bandwidth of the complex LPGAC to be injected into the input port of waveguide 1, as shown in Fig. 4(a). By turning on the optical pump to make the gain perturbation matched with the refractive index modulation ($k_\alpha/k_n = 1$), the complex LPGAC not only transfers the input signals to the output port of waveguide 2, but also provides an amplification to the signals' power (as shown in Fig. 2(g)). Then, the signals will be transmitted along the self-closed loop and arrive in the input port of waveguide 2 with some attenuation. Because coupling behavior are checked when signals are injected from waveguide 2 in the case of $k_\alpha/k_n = 1$, the signals cannot be transferred back to waveguide 1. Thus, the signals will be circulated and stored in the self-closed loop. Figure 4(b) shows the signals after circulating two roundtrips. When the stored signals need be picked up and exported from the loop, we can turn off the optical pump to make the complex LPGAC become the conventional LPGAC ($k_\alpha = 0$ but $k_n \neq 0$). The reciprocal and symmetric power coupling action (as shown in Fig. 2(b)) will transfer the stored signals from input port of waveguide 2 to the output port of waveguide 1, as depicted in Fig. 4(c). Therefore, signals can be buffered or picked up discretionarily by controlling the optical pump.

5 Conclusions

In this paper, based on the unified coupled-mode equations, influences of gain/loss perturbation on the performance of complex LPGAC are investigated in detail. Results demonstrate that a unique unidirectional nonreciprocal power coupling can be realized by matching gain/

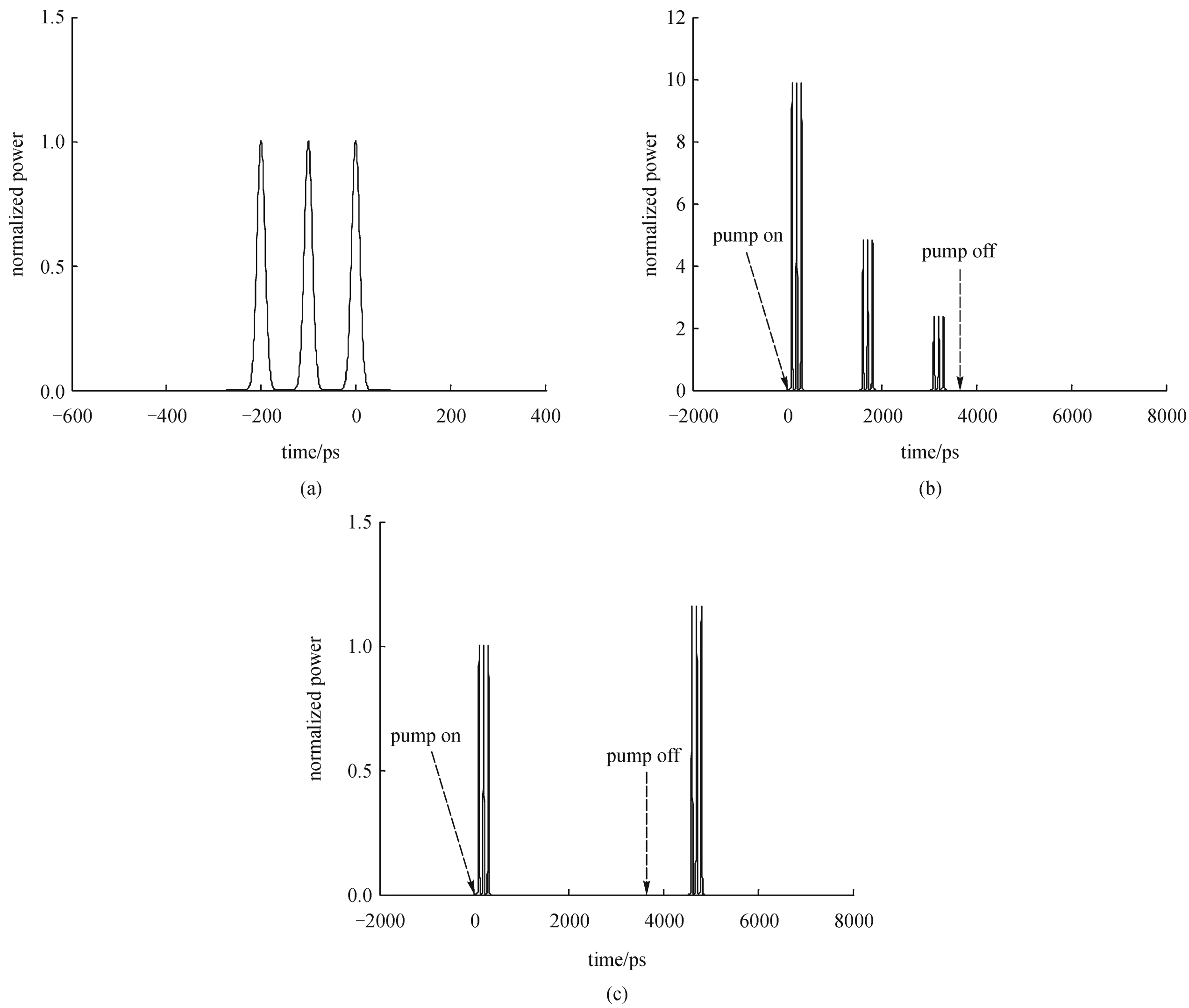

Fig. 4 (a) Pulse signals in input port of waveguide 1; (b) pulse signals buffered in self-closed loop; (c) pulse signals picked up at output port of waveguide 1

loss with the refractive index modulation. And a novel optical signal buffer combined the complex LPGAC with a self-closed loop is proposed. This compact low-cost device will have many attractive applications in the future all-optical network.

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