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A wide-band polymeric electro-optic modulator array based on unidirectional coupling between multi-mode waveguide array and a vertical configured dumping planar waveguide

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Abstract

A polymeric wide-band electro-optic (EO) modulator array based on unidirectional mode-coupling between the guiding multi-mode waveguide array and a vertical configured planar dumping waveguide was developed. A low insertion loss of <1.7 dB was obtained due to asymmetrically designed guiding waveguide and the dumping waveguide. A modulation depth of 91% was achieved with the device length of 3.5 cm at a low driving voltage of 3.2 V. The employment of the dumping planar waveguide not only provides an efficient way to achieve the unidirectional coupling mechanism, but also effectively confines the light coupled from the guiding waveguides within the planar dumping waveguide. The combination of unidirectional coupling and light confinement effects ensures low cross talk of <22 dB between adjacent guiding waveguides. Since the proposed modulator is based on the unidirectional coupling mechanism, it is intrinsically wide-band. A wide-band operation from 1308 to 1324 nm was experimentally obtained. The unidirectional mode-coupling-based wide-band modulation principle can be readily applied to other wavelengths, such as 1330 and 1550 nm ranges.

Keywords: Electro-optical modulator; Photonic devices; Unidirectional coupling polymer waveguide; Multi-mode waveguide; Wide-band modulator; Optical network

1. Introduction

The proliferation of data, voice, and video communications has strained the capacity of conventional networks and motivated research on all-optical networks [1–3]. In all-optical networks, wavelength division multiplexing (WDM), optical switching and wavelength routing technologies are employed to multiplex/demultiplex, reroute and split or tap optical signals to different networks and nodes [4–6]. To make the WDM optical networks reconfigurable and reduce the high costs associated with individual designs and fabrications of different wavelengths, tunable laser sources and wide-band electro-optic (EO) modulator are highly desired for low-cost metro-optical networks.

Polymeric single-mode optical waveguide-based EO modulators have been investigated and high modulation bandwidth (>10 Gbit/s) has been demonstrated [7–9]. However, most of the demonstrated polymer waveguide modulators are based on interference mechanism, which is intrinsically wavelength sensitive. The wavelength sensitivity not only introduces design and fabrication difficulties, but also seriously limits the modulator's application in dynamic reconfigurable optical network. To address the wavelength sensitivity issue, we have

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developed an EO modulator based on a unidirectional coupling mechanism [10,11]. In this paper, we present a wide-band EO modulator array based on the unidirectional coupling mechanism. A low insertion loss of <1.7 dB was obtained due to asymmetrically designed guiding waveguide and the dumping waveguide. A modulation depth of 91% was achieved with the device length of 3.5 cm at a low driving voltage of 3.2 V. A low cross talk of <22 dB between the guiding waveguides was achieved due to the unidirectional coupling mechanism and the effective light confinement provided by the dumping planar waveguide. Since the proposed modulator array is based on the unidirectional coupling mechanism, it is intrinsically wide band. A wide-band operation from 1308 to 1324 nm was experimentally demonstrated. Based on the same unidirectional mode-coupling-based wide-band modulation principle, wide-band EO modulators working other wavelengths, such as 1330 and 1550 nm ranges can be achieved.

2. Device design based on the unidirectional coupling mechanism

The schematic structure of the device is shown in Fig. 1. The device consists of a multi-mode waveguide array designed for guiding optical signals, top and bottom modulating electrodes, and a planar dumping waveguide under the guiding multi-mode waveguide. The guiding multi-mode waveguides and the dumping planar waveguide, separated by a low-index polymer buffer layer, are intentionally designed to have different effective indices, which introduces coupling modes phase-mismatches between the guiding waveguides and the planar waveguide. The phase-mismatches ensure a low insertion loss for each guiding waveguide. The dumping planar waveguide was designed to be lossy (>6.5 dB/cm) such that optical energy coupled from the guiding multi-mode waveguide can be efficiently dumped out; thus, a unidirectional coupling mechanism [11] can be achieved.

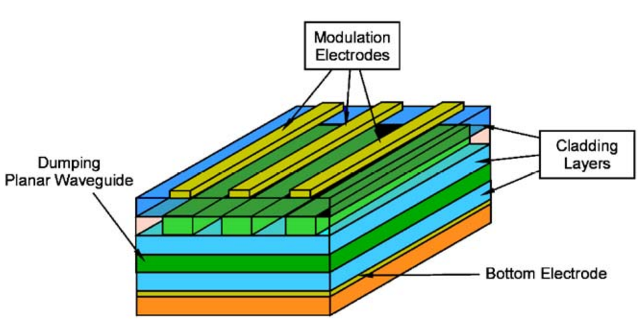

Fig. 1. Schematic structure of the multi-mode waveguide-based EO modulator array.

The unidirectional coupling equations can be written as [11]

$$2(\mathrm{i}\beta_n - \alpha_n)\frac{\mathrm{d}A_n}{\mathrm{d}z} + \kappa_{mn}A_m(z)\,\mathrm{e}^{(\alpha_m-\alpha_n)z}\,\mathrm{e}^{\mathrm{i}\Delta z} = 0, \tag{1}$$

$$2(\mathrm{i}\beta_m - \alpha_m)\frac{\mathrm{d}A_m}{\mathrm{d}z} + \kappa_{nm}A_n(z)\,\mathrm{e}^{(\alpha_n-\alpha_m)z}\,\mathrm{e}^{-\mathrm{i}\Delta z} = 0, \tag{2}$$

where κ_{mn} is the coupling constant between the guided modes of the guiding waveguide and the planar waveguide, $\Delta = \beta_m - \beta_n$ is the phase-mismatch, and β, α are the propagation constant and the loss coefficient, respectively. Ignoring the loss of the guiding waveguide, α_n, i.e. $\alpha_n \approx 0$, and solving the differential Eqs. (1) and (2), one can get

$$A_n(z) = \mathrm{e}^{-(\mathrm{i}\Delta+\alpha/2)z}[A\,\mathrm{e}^{(c+\mathrm{j}d)z} + B\,\mathrm{e}^{-(c+\mathrm{j}d)z}], \tag{3}$$

$$c = \frac{1}{2}\mathrm{Re}\left[\sqrt{\alpha^2 - \Delta^2 - \frac{|\kappa|^2}{1+(\alpha_m/\beta_m)^2} + \mathrm{i}\left[2\Delta\alpha_m + \frac{|\kappa|^2\alpha_m/\beta_m}{1+(\alpha_m/\beta_m)^2}\right]}\right], \tag{4}$$

$$d = \frac{1}{2}\mathrm{Im}\left[\sqrt{\alpha^2 - \Delta^2 - \frac{|\kappa|^2}{1+(\alpha_m/\beta_m)^2} + \mathrm{i}\left[2\Delta\alpha_m + \frac{|\kappa|^2\alpha_m/\beta_m}{1+(\alpha_m/\beta_m)^2}\right]}\right]. \tag{5}$$

Considering the boundary condition $(\mathrm{d}/\mathrm{d}z)A_n(z)|_{z=0} = 0$, one get

$$B = A\frac{(-\alpha_m/2 + c) + \mathrm{j}(d - \Delta/2)}{(\alpha_m/2 + c) + \mathrm{j}(d + \Delta/2)}. \tag{6}$$

Substituting (4), (5) and (6) into (3), one get the intensity of the light:

$$\begin{aligned} I_n(z) &= |A_n(z)|^2 \\ &= \mathrm{e}^{-\alpha z}|A|^2\left|\mathrm{e}^{(c+\mathrm{j}d)z} + \frac{(-\alpha_m/2 + c) + \mathrm{j}(d - \Delta/2)}{(\alpha_m/2 + c) + \mathrm{j}(d + \Delta/2)}\,\mathrm{e}^{-(c+\mathrm{j}d)z}\right|^2. \end{aligned} \tag{7}$$

The intensity of light in the guiding waveguides is shown in Fig. 2. Notice that when phase-matched and the planar waveguide is lossy, high-efficiency unidirectional coupling can be achieved. When the coupling is phase-mismatched, less than 1 dB power coupling loss to the dumping waveguide can be obtained with the device length of 3.5 cm.

According to the simulation, shown in Fig. 2, the guiding waveguide and the planar waveguide of device are intentionally designed to have a large phase-mismatch between the modes of the guiding waveguide and the planar waveguide. The phase-mismatch ensures a low mode-coupling loss of <1 dB. The EO-induced index change modulates the phase-mismatch and thus the coupling efficiency. When phase-matching condition is satisfied, efficient unidirectional coupling to the