Slow Light Enhanced E-O Polymer Nano-Photonic Modulator with Ultra-High Effective In-Device r_{33}

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Abstract: We demonstrate an E-O polymer infiltrated silicon photonic crystal slot waveguide modulator. Enhanced by improved poling efficiency and slow light effect, we achieve an ultra-high effective r_{33} of 735pm/V and $V_{\pi}L$ of only 0.44Vmm.

OCIS codes: (230.4110) Modulators; (230.5298) Photonic crystals

1. Introduction

Electro-Optic (E-O) polymer modulators have demonstrated exceptional performances for ultra-high bandwidth [1] and sub-volt half-wave driving voltage (V_{π}) [2]. However, the E-O efficiency of polymer photonic devices cannot exceed the thin film r_{33} value due to the presence of bottom and top cladding layers. The flourish of silicon nano-photonics, especially silicon slot waveguide [3] and photonic crystal waveguides [4], provides a platform for E-O polymer integration into nano-meter scale, which can achieve significantly higher E-O efficiency than conventional E-O polymer photonic devices. Photonic devices based on silicon/E-O polymer hybrid material system combine strong optical confinement abilities of silicon with superior E-O modulation efficiency of polymers. Compared with conventional E-O polymer photonic devices, this hybrid approach requires no cladding polymer layers, which should lead to higher E-O efficiency. In this paper, we present the design and experimental demonstration of an E-O polymer nano-photonic modulator using 320nm photonic crystal slot waveguide, which is the widest slot waveguide that has ever been reported. The wider slot reduces the leakage current by nearly two orders of magnitude and improves the effective in-device r_{33} to 735 pm/V. To the best of our knowledge, this is the highest E-O efficiency of polymer photonic devices that has ever been reported.

2. Design and Fabrication

Figures 1 (a) shows the scanning electronic microscopy (SEM) image of the transitional region from silicon strip waveguide to photonic crystal slot waveguide using an optical mode converter and photonic impedance taper. The nano-photonic modulator is fabricated on a silicon-on-insulator (SOI) wafer with 230nm thick lightly doped p-type top silicon layer. The input and output waveguides use conventional silicon strip waveguide. The modulation region with slot nanostructures are formed in a hexagonal lattice photonic crystal slab with a lattice constant a=425nm and hole diameter d=297nm. The photonic crystal waveguide is a standard W1.3 waveguide by replacing a line of air holes with a slot of w=320nm. The modulation region consists of 800 periods of photonic crystals, thus the total modulation length is 340μm. The silicon photonic crystal regions including air holes and the slot are fully covered by polymer materials with strong E-O coefficient consisting of a guest host system of 25% weight chromophore AJ-CKL1 into amorphous polycarbonate (APC). The refractive index of the infiltrated polymer is n=1.63 at 1.55μm wavelength. The associated band diagram of the guided mode is displayed in Figure 1 (b). It is seen that the photonic crystal slot waveguide will support multiple guided modes. The optical intensity profiles ($|E_x|^2$) of these guided modes at the band edge (wave vector of π/a) are simulated by three-dimensional planar wave expansion (3-D PWE) method and are also shown in the Figure 1(b) insets. Only the fundamental mode is useful for our nano-photonic modulator. The optical power concentrated in the 320nm slot is around 35% of the total optical power.

The fabrication procedures of the nano-photonic modulator are described in [5]. After infiltrating AJCKL1/APC, the sample is heated to the glass transition temperature (T_g=145°C) of the guest/host polymer while 100V/μm poling field is applied. The leakage current during the poling process is monitored in situ as shown in Figure 1 (c) for the 75nm and the 320nm slot waveguide. The peak current for the 75nm slot waveguide is 4.5×10^{-8}A, while it only 6.2×10^{-10}A for the 320nm slot. If we assume the leakage current only goes through the slot waveguide, and with a cross sectional area of 340μm×0.23μm, the current density of the E-O poling process is 575A/m^2 and 7.9A/m^2 for the 75nm and the 320nm slot, respectively. Comparing with the typical 1~10A/m^2 leakage current of thin film AJCKL1/APC [6], the 320nm slot waveguide shows approximately an ideal E-O poling behavior as that of the thin film material.

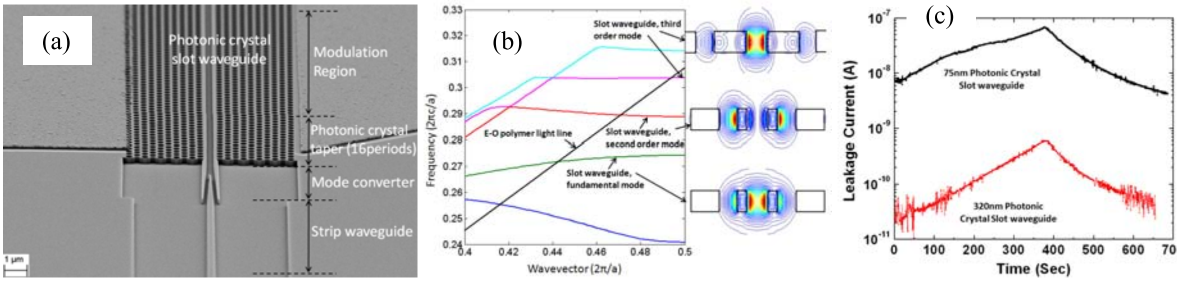

Figure 1 (a) SEM picture of the 320nm wide silicon photonic crystal slot waveguide (b) Photonic band diagram and optical mode profiles of the 320nm wide photonic crystal slot waveguides (c) Leakage current during the poling process for the 75nm and the 320nm photonic crystal slot waveguide infiltrated with AJCKL1/APC

3. Measurements

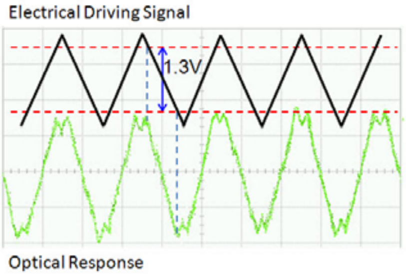

Figure.2 Low frequency modulation measurements showing a low V_π of 1.3V for the E-O polymer nano-photonic modulator with 340µm modulation arm

In the measurement, the output of the laser source is tuned to 1540 nm wavelength, where maximum modulation response is achieved. The E-O polymer nano-photonic modulator was driven by a 100 KHz triangular wave with a peak-to-peak voltage V_{pp} of 1.7V. The waveform from a digital oscilloscope in Figure 2shows that over modulation occurs at 1.3V, which is the V_π of the E-O polymer nano-photonic modulator. The effective in-device E-O coefficient is calculated as

$$r_{33} = \frac{\lambda w}{n^3 V_\pi \Gamma L} = \frac{1540nm \times 320nm}{1.63^3 \times 1.3V \times 0.35 \times 340\mu m} = 735\,pm/V$$

Comparing with the 70pm/V r_{33} of the thin film AJCKL1/APC [6], our effective in-device E-O efficiency is ten times higher than that of the thin film material. Usually the in-device r_{33} of E-O polymer modulators is lower than that of the thin film material. This extraordinarily high r_{33} value proves the combined enhancement of slow light effect and an increased poling efficiency. The nano-photonic modulator also achieves very high modulation efficiency with V_π•L=0.44V•mm

This $V_\pi L$ is the best result for all E-O polymer photonic modulator that has ever been reported. To evaluate the poling efficiency of the E-O materials, we calculated the group index of the photonic crystal slot waveguide to be n_g=36, which gives a slow light enhancement factor of 12.4, so we can conclude that the material r_{33}=59pm/V for 320nm slot, while r_{33}=11pm/V for 75nm slot.

4. Conclusion

In summary, we have achieved 735pm/V effective in-device r_{33} and 0.44Vmm $V_\pi L$, all of which are the best results that have ever been reported. These improvements are attributed to the increased poling efficiency of the E-O polymer inside the 320nm photonic crystal slot waveguide. By further optimizing the poling process through modified surfaces or improved E-O polymer materials, we believe that E-O polymer infiltrated silicon photonic crystal slot waveguide could even exceed current performances.

5. References

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