Electro-Optic Devices with Nanometer Scale Structures Fabricated by Electron Beam

CNF Project # 1600-07
Principal Investigator(s): Antao Chen
User(s): Antao Chen

Affiliation(s): Applied Physics Laboratory, University of Washington
Primary Research Funding: Department of Defense
Contact: antaochen@apl.washington.edu
Web Site: http://photonics.apl.washington.edu

Abstract:

Decomposition of chromophore molecules under direct electron beam irradiation reduces the refractive index of chromophore containing polymers. The induced refractive index contrast between the exposed and unexposed regions is high enough for waveguide bends of small radius and thus micro-ring resonator devices. This electron beam bleaching of chromophore-containing polymers provides a fabrication approach for nonlinear polymer optical waveguide devices. Fabrication of high quality micro-ring resonators with critical feature size on the order of 100 nm was demonstrated with this technique in a PMMA electron-beam resist that contains nonlinear optic chromophores.

Summary of Research:

Photonic integration can provide size, weight, and power (SWAP) reductions together with better performance analogous to electronic integration. Micro-ring resonators are regarded as the promising building blocks because of their compactness and multifunctionality. For example, versatile functions of electro-optic modulation and switching, optical rectification, wavelength conversion and all-optical switching can be realized by micro-ring resonators made of organic nonlinear optical materials [1]. Exponential increasing of the electro-optic coefficients in a rate consistent with Moore’s Law and the intrinsic ultrafast response time of these materials could allow for ‘lossless’ conversion or even gain in the electrical-optical-electrical signal transduction process and terahertz bandwidths.

Typical organic nonlinear optical materials are guest-host systems with optical polymers doped with organic chromophores. Systematic analysis and simulation of polymer micro-ring resonators shows that fabrication of the submicron coupling gap with a precision < 100 nm is critical to achieve high quality factor (Q-factor) and sharp resonance. This high resolution can be achieved through electron beam lithography combined with reactive ion etching (RIE) or nanoimprinting. Traditional photolithography plus RIE have also been used to fabricate micro-ring resonators with lateral coupling gaps greater than 1 μm or vertical coupling gaps. However, many device designs require lateral coupling gaps smaller than 2 μm. For the chromophore-containing polymers, we have found that high energy electron beam can break bonds and decompose the organic chromophores. This decomposition bleaches out the color and reduces the index of refraction of the polymers. Electron beam irradiation induced a refractive index decrease of about 0.06 in chromophore-containing polymethyl methacrylate (PMMA) polymers, which is large enough for ring waveguides of small radius. Electron beam provides nanometer scale resolution, which couldn’t be achieved with photobeaching. Without using expensive high resolution photomasks, different designs of micro-ring resonator devices can be generated easily with computer assisted design and control systems. This is especially cost effective for device prototyping and design optimization. Electron beam bleaching is a single step process, which simplifies the device fabrication and reduces the sources of error from multiple fabrication steps. It also eliminates the use of wet chemicals which can dissolve the chromophore-containing polymer waveguides and greatly increase the propagation loss.
Electron beam bleaching of the electro-optic polymer was used to make micro-ring resonators of the basic structure with a single ring resonator coupled to one bus waveguide. The electron beam dose was also 700 µC/cm². Si substrate with a 5 µm thermal silicon dioxide layer was used. The silicon dioxide was used as the lower cladding and its refractive index is 1.46.

The highest resonance extinction ratio was achieved in a micro-ring resonator with a waveguide width of 5 µm, total width including waveguides and the two exposed strips of 100 µm, and coupling gap size of 200 nm. The ring resonator had a racetrack shape with circular sections of 500 µm radius and straight coupling section of 100 µm in length, as shown in Figure 1. The extinction ratio was 12 dB for TE polarization and 9 dB for TM polarization. The resonance spectrum of the TE polarization was fitted to the theoretical transfer function as shown in Figure 2. The fitted internal circulation attenuation factor $\alpha$ is 0.55 and coupling attenuation factor $t$ is 0.36. From these fitting results, $Q$-factor was calculated to be 9450, ring waveguide propagation loss 16 dB/cm, and finesse 2.7.

In conclusion, decomposition of chromophore molecules under electron beam irradiation reduces the refractive index of the chromophore containing polymers. The refractive index change by electron beam bleaching is large enough for small waveguide bending and thus micro-ring resonator devices. The electron beam bleaching techniques was used to directly write micro-ring resonators of high extinction ratio and quality factor. Electron beam bleaching is a single step, maskless, resistless direct writing process. Future work will be realizing micro-ring resonator devices with the functions of electro-optic modulation, switching and tunable filtering using this technique.

References: