Wavelength and Bitrate tunable silicon-organic hybrid modulator using commercially available HLD.

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Abstract

In the field of on-chip photonic modulators, we introduce an innovative design that harnesses the exceptional properties of a newly developed chromophore called HLD (Nonlinear Materials Corporation). This chromophore boasts remarkable features, such as a high r33 value of 290 pm/V, a high transition temperature (Tg) of 1500°C, and seamless integration with CMOS technology. This work discusses the design of a Si waveguide modulator incorporating a set of 1 D Bragg filters using 3 Si-HLD bilayers with a central Si defect region forming a wavelength-selective Fabry Perot cavity. On application of voltage to the electrodes on either side of the waveguide, the Pockel effect-induced index change of the HLD in the Bragg filter will selectively transmit wavelength in the C and L bands. The voltage range used for tuning in the C & L band is 0.1 to 1 V. This design has a maximum wavelength tuning of 690nm within this range. This design paradigm can be extended for on-chip amplification and holds great promise in advanced photonic applications.

Keywords: On-chip photonic modulators. HLD, Pockels effect

Introduction

The photonics telecommunication systems must cater to the growing demand for low-cost, high-speed, and high-bandwidth devices. Complex signal processing methods allowing the use of multiple degrees of freedom (such as frequency, polarization/mode, phase, and amplitude) within a single signal are used to improve network data-carrying capacity. Electro-optic modulators are widely used in telecommunications systems to encode information into optical signals. By varying the applied voltage, the refractive index of the material changes accordingly, which modifies the phase or intensity of light passing through it. This modulation allows for power-efficient encoding of data. In the context of increasing demand and requirement of flexible provisioning, there is a strong focus on adaptive devices that provide modulation and multiplexing techniques to increase the speed, or efficiency of devices keeping power and real estate requirements low. Organic electro-optic (OEO) materials have emerged as a particularly promising avenue due to their potential applications in ultrahigh-speed and energy-efficient data transmission and signal processing. These materials are advantageous for chip-scale integration, offering superior electro-optic activity, response times, and bandwidth when compared to traditional inorganic electro-optic materials. Current on-chip photonic modulator designs primarily utilize non-linear optical (NLO) material stacks like LiNbO3 or BaTiO3 on silicon, or they rely on injecting current into silicon waveguides to induce the required phase change for optical modulation[1][2]. Another explored option compatible with silicon involves using silicon-slotted waveguides filled with organic NLO materials within the slots. However, challenges include the photostability, thermal stability, and low transition temperatures (Tg) of these organic materials, as well as fixed operating wavelengths imposed by waveguide design constraints.

To address these limitations, significant efforts have been devoted to enhancing chromophores with higher NLO activity and increased Tg. A recently introduced chromophore, known as HLD marketed by Nonlinear Material Corporation, has garnered attention for its exceptional properties. HLD can operate at temperatures as high as 1500°C and seamlessly integrates with CMOS technology. It exhibits a substantial Pockel effect with a high r33 value of 290 pm/V, possesses a Tg of 1500°C, and maintains a refractive index within the range of 1.83-1.85. Consequently, due to its high figure of merit, HLD requires deficient voltage levels to induce an effective refractive index change. Importantly, HLD can be applied through spin coating or in-situ growth from powder, eliminating the need for a host polymer and ensuring compatibility with CMOS processes.[3]

This research centres on the design of a silicon waveguide modulator that incorporates a set of one-dimensional Bragg filters utilizing three Si-HLD bilayers. This configuration creates a wavelength-selective Fabry-Perot cavity. When a voltage is applied to the electrodes on either side of the waveguide, the Pockel effect-induced refractive index change of HLD within the Bragg filter selectively transmits wavelength in the C&L band. The device's dimensions have been meticulously optimized to prevent any wavelength transmission in the 1530-1570nm range when no voltage is applied, effectively assuring zero optical output for a bit voltage of 0. Desired transmission wavelengths can be adjusted by applying the appropriate voltage to the electrodes.

Thus, when an RF signal is applied to the electrodes, the device produces optical output when the bit is high, with the voltage level corresponding to the high bit variation also selecting a specific wavelength. This feature, coupled with the use of a low-cost broadband super luminescent LED source, allows for wavelength selection within the 0.1 to 1V voltage range. Notably, the high femtosecond (fs) response time of HLD enables modulation capabilities of hundreds of gigahertz (GHz). This design can be further adapted to accommodate different materials that offer gain and serve as on-chip amplifiers.[4]

In summary, this work addresses the limitations of existing on-chip photonic modulator designs by introducing HLD, a cutting-edge chromophore. The integration of HLD into a silicon waveguide modulator result in enhanced performance, dynamic wavelength tuning, and high-frequency modulation capabilities. This design holds promise for various photonic applications, including data communication and signal processing

Theory

When an external voltage is introduced to a nonlinear material, alterations in its refractive index occur predominantly due to two significant factors: the Pockels effect (Δn_p) and the Kerr effect (Δn_k).

$$\Delta n = \Delta n_p + \Delta n_k \quad \text{-------- (1)}$$

If the change in a material's refractive index is directly proportional to the applied electric field and is determined by the second-order susceptibility, we are observing the Pockels effect. The calculation of the refractive index change (Δn_p) due to the Pockels effect can be expressed using this equation.

$$\Delta n_p = -\frac{1}{2} \times n^3 \times r_{33} \times \frac{V}{d} \quad \text{------- (2)}$$

where r33 is the electro-optic coefficient, V is the applied voltage, d is the distance between the electrodes, and n is the effective refractive index.

In Kerr effect, exhibited by non-centrosymmetric materials, changes in the refractive index is determined by the square of the applied electric field and material's third-order susceptibility (χ^3), which is much lower in magnitude than χ^2. Therefore, the Kerr effect is considerably less pronounced than the Pockels effect. So, equation (1) can be written as,

$$\Delta n = \Delta n_p \quad \text{------- (3)}$$

The key feature of Si-EO hybrid devices is the ability to control the refractive index of the EO material by applying an external voltage. When an electric field is applied to the EO material, it changes its refractive index, which, in turn, affects the propagation of light through the device. This voltage-dependent control allows for dynamic tuning of the device's optical properties. The EO tuning of the device is modelled using an equation that depicts the pocket-effect-induced change in RI of the HLD upon voltage application.[5]

$$\Delta n_{HLD} = -\frac{n_{HLD}^3 \gamma^{33} f^3 V}{2d} \quad \text{------(4)}$$

Where, Δn_{HLD} is the change in the refractive index of HLD, γ^{33} is the EO Coefficient, V is the applied voltage, d is the separation between electrodes, and f (6.1) is the field factor.[5][6]

The HLD chromophore material is intended to serve as both a cross-linker and an EO-active component. Since no polymer cross-linker is required, a high chromophore loading can be maintained, and r33 is proportional to chromophore concentration. The dipole moments of the EO chromophores must be aligned to the external field to ensure non centrosymmetric orientation for it to exhibit EO activity. For this the material is heated to its glass transition temperature (Tg = 1500^0C). This temperature is typically below the material's melting point but high enough to allow the material's molecules to move more freely. While the material is at or near its Tg, a strong DC electric field is applied across it. This electric field induces the alignment of the dipole moments of the electro-optic chromophores within the material. The material is then cooled while maintaining the applied electric field. As it cools, the dipole moments become "frozen" in their aligned state, leading to the desired molecular order and EO activity within the material. It's important to note that the molecular alignment and EO activity induced by electric field poling is stable if the material is not heated to or near its Tg again. Heating it to Tg or above can disrupt the dipole moment alignment, causing the material to lose its EO activity.[7][8][9]

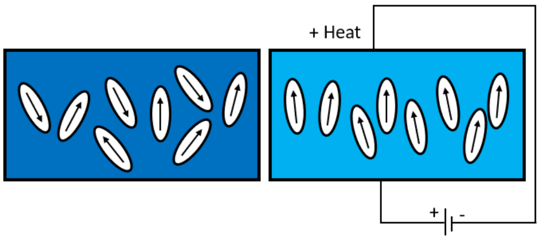

Figure 1: Electric field poling process to orient chromophore molecules.

Device Design

For the proposed device, the initial optimization of dimensions of the Bragg layers with central defect to ensure target transfer function, is carried out in MATLAB to save computational resources. The structure is then incorporated within the silicon waveguide and the actual device with the electrodes for applying field is then simulated and optimized further in COMSOL. Here, the defect introduced in between the Bragg structure results in a Fabry Perot resonator filter with the mirrors on either side of the conventional bulk Fabry Perot cavity replaced by Bragg filters. The Bragg layers are designed in such a way that their width along the propagation direction of light is essentially integral multiples of quarter-wave satisfying the condition for Bragg reflection with the central region being integral multiples of half the wavelength that needs to be transmitted. The design reported here has Bragg layers of 155nm wide silicon alternating with 250nm wide HLD layer. The central Si defect region, together with the 1D Bragg filters and Si-HLD bilayers, forms a Fabry-Perot cavity that selectively resonates at specific wavelengths in this design. This means it strengthens or weakens light at those specific wavelengths, making it suitable for a variety of optical applications such as wavelength filtering or modulation. The device dimensions are shown in Figure 2.

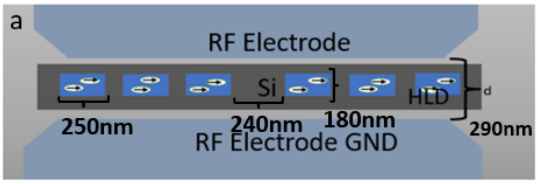

Figure 2: Design of the proposed Si-EO modulator.

Simulation

Finite Element Analysis (FEM) is a numerical method to solve complex partial differential equations describing physical processes. COMSOL® employs FEM to model and analyze the behavior of the photonic device. While the actual device may be three-dimensional (3D), performing a full 3D simulation can be computationally intensive and time-consuming. This work uses a 2D simulation approach to reduce computational requirements while providing valuable insights into the device's behavior. COMSOL offers various specialized modules for different physics domains. This work uses the "Wave Optics" and "AC/DC" modules. The electrodes in the simulation are treated as perfectly electric conductors. This simplifies the boundary conditions and ensures that the electrodes have negligible electrical resistance. Meshing is a crucial step in FEM simulations. A "standard physics-controlled mesh" indicates that COMSOL automatically generates an appropriate mesh based on the physics of the problem, ensuring accurate results. In this case, the sweep covers a wavelength range from 1500nm to 1700nm, to explore the device's performance over different optical wavelengths. User-defined parameters such as wavelength, voltage, electrode spacing, and material properties (refractive index of HLD and EO coefficients) are defined under "global definitions." This allows for easy and efficient manipulation of these parameters during simulations or optimizations. Table 1 below provides the transfer function simulation results for various voltages, and Figure 3 shows an example of a transfer function at 0.8 V. There are simultaneous peaks on both the C and L bands for the same voltage.

Voltage (V)	Wavelength (nm)	Transfer function	Wavelength (nm)	Transfer function
0.1	1558	0.90	1639	0.85
0.2	1551	0.90	1628	0.87
0.3	1545	0.91	1619	0.86
0.4	1539	0.91	1610	0.87
0.5	1533	0.91	1602	0.87
0.6	1528	0.91	1595	0.87
0.7	1524	0.93	1588	0.88
0.8	1519	0.92	1582	0.88
0.9	1515	0.92	1576	0.89
1.0	1512	0.92	1571	0.89

Table 1: Simulation Results of the transfer function for different wavelengths.

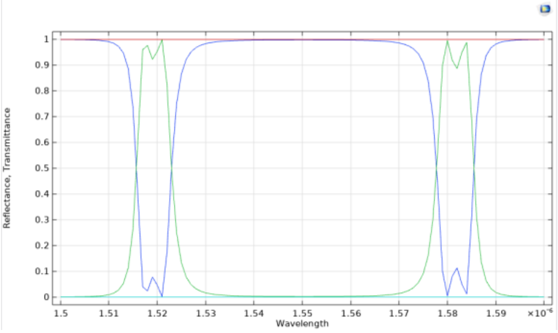

Figure 3: Reflectance (blue) and Transmittance (green) as a function of wavelength for 0.8 V from COMSOL®

Results

COMSOL® Multiphysics software is used to design a silicon HLD waveguide filter. Figure 4 shows the simulation result of the proposed model. In Figure 5, we can observe the transmission spectrum, which portrays how the filter performs at different applied voltages and wavelengths within the C-band (shown in the line graph) and L-band (indicated by the dotted graph). It is worth noting that the application of a single voltage setting can lead to tuning in both the C and L bands. If the source only covers the C-band, there will be tuning specifically in that band.

Conversely, if the source is a full broadband source, both one C-band and one L-band will be transmitted simultaneously. By applying the appropriate voltage to the electrodes, it is possible to alter the desired wavelength of transmission. This design has a maximum wavelength tuning of over 690nm within 1 Volt. COMSOL® serves as a valuable tool to assess such tuning capabilities with capturing the effective mode index in the waveguide and ensuring optimal performance.

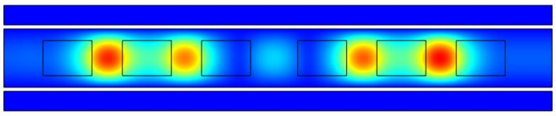

Figure 4: Wavelength transmission at 0.8V.

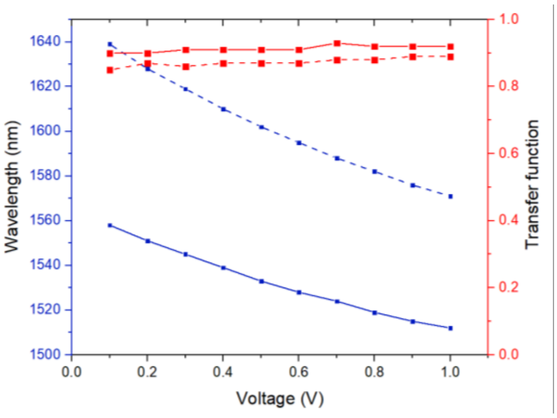

Figure 5: Voltage tuning curve and transfer function for Si-EO Wavelength selective waveguide

Conclusions

We present a silicon electro-optic modulator's concept, design, and simulation for use in optical phase modulation applications. In this study, a Si waveguide modulator with three Si-HLD bilayers and a central Si defect region that forms a wavelength-selective Fabry Perot cavity is designed. It includes a set of one-dimensional Bragg filters. Combination of device design and HLD ensures low tuning voltage requirements, we of 0.1- and 1-volts. JRD is another material manufactured by the same company, so by changing the r33 value, the voltage level will scale accordingly as the refractive index of JRD is also within the same range as HLD. But the comparatively low T_g of JRD may limit its practical application. Appropriate modification of this design to include materials that can provide gain can lead to devices that can function as an on-chip amplifier.

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