Slow light-assisted 1D slotted Fishbone Photonic Crystal for Optical Biosensing and Spectroscopy Applications

Sourabh Jain[1,2,*], Santosh kumar[2], May Hlaing[3], Jason Midkiff[3], Kang-Chieh Fan[1], and Ray T. Chen[1,3,†]
[1]*Department of Electrical and Computer Engineering, University of Texas at Austin, TX 78758, USA*
[2]*Centre of Excellence for Nanotechnology, Department of Electronics and Communication Engineering, Koneru Lakshmaiah Education Foundation, Vaddeswaram, Andhra Pradesh–522302, India*
[3]*Omega Optics, Inc., 8500 Shoal Creek Blvd., Bldg. 4, Suite 200, Austin, Texas 78757, USA*
Author e-mail address: [†]chenrt@austin.utexas.edu, [*]sourabhjain@kluniversity.in

Abstract: A slotted fishbone design is proposed as a slow-light enhanced 1D-photonic-crystal on a silicon-on-insulator platform for spectroscopy and biosensing applications. Theoretical studies reveal a high group index of 68 with a strong field confinement of 40% in the cladding region.

1. Introduction

The ability to slow down light has garnered significant attention due to its wide-ranging applications in fields such as classical and quantum nonlinear optics, quantum information processing, optical communication, and optical biosensing and spectroscopy applications [1]. On-chip slow light can be achieved using photonic crystal waveguides (PCW), which leverage strong modal dispersion near the band edge to reduce group velocity. In photonic systems, such a phenomenon has led to advancements in applications like high-sensitivity sensing, optical switching, and time-delaying. It has also been explored for enhancing nonlinear effects such as frequency comb generation and improving interferometric sensitivity [2]. By engineering photonic structures, one can achieve slow light effects in on-chip devices, paving the way for miniaturized and integrated photonic technologies.

While two- and three-dimensional photonic crystals have been widely studied for slow light applications, their complex fabrication and integration processes with standard on-chip components such as rib/ridge waveguides, slot waveguides, and couplers present significant challenges [3]. In contrast, one-dimensional (1D) photonic crystal structures offer notable advantages, including simpler fabrication, reduced device footprint, and ease of integration with other photonic components. These structures can effectively produce slow-light effects near photonic bandgaps, making them ideal for sensing and modulation applications. Riboli et al proposed a theoretical analysis on a bandgap-engineered coupled resonator optical waveguide and demonstrated 10 times slower wave propagation compared to free space light [4]. Recently, Morán et al. demonstrated slow-light behavior utilizing bimodal interferometric characteristics in 1D PCWs at telecommunication wavelengths [3].

Our group has also contributed significantly to this field, successfully demonstrating several slow-light-assisted photonic structures for various applications. Previously, we proposed a fishbone-style 1D PCW as a true-time optical delay line and practically achieved a delay time of 65 ps/mm to free space light velocity [5]. However, the strong light confinement in the high-dielectric core waveguide is unsuitable for sensing applications. This limitation arises because, despite the impressive slow-light effect within the waveguide, only a weak evanescent field interacts with the cladding analyte. To address this, it is desirable to design a structure that combines slow-light characteristics with high modal field overlap in the cladding region (i.e. the sensing region) to maximize photon-analyte interaction for sensing applications. A slot waveguide is a prominent solution for guiding light in a low-index region, with a strong electric field concentrated in the slot region, which significantly enhances the sensing performance. Several studies on slotted photonic crystal structures have leveraged slow-light characteristics in the slot region, including our work on electro-optic (EO) polymer-based optical modulators [6]. The challenge with slot waveguides is to efficiently couple light from fiber to chip and vice versa due to the modal-size mismatch between the ridge waveguide and the slot waveguide. We have also addressed such issues utilizing an adiabatic mode converter, which only costs 0.08dB insertion loss [7]. Another challenge with the slow-light waveguide is group index (n_g) mismatching which has been handled with the tapered n_g mechanism to minimize the coupling loss [8]. In this work, we propose a CMOS-compatible and single-mask implementable slow-light assisted fishbone-style 1D slotted photonic crystal waveguide as a sensor to leverage the benefit of both high group index and high light confinement in the cladding region. Considering the slow-light feature and optical mode confinement in the cladding region (Γ_{air}), our optimized structure achieves up to 27 times the light-analyte interaction occurring with an equivalent field in free space. This characteristic greatly enhances the interaction between light and analytes, making it highly suitable for advancing on-chip biosensing and spectroscopy applications.

2. Device Design and Working

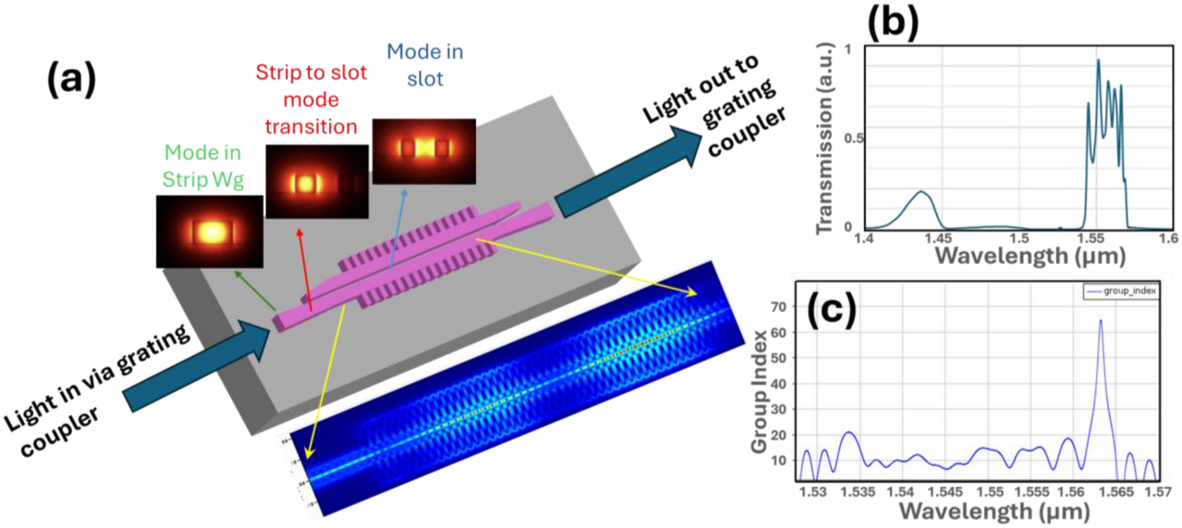

Fig: 1(a) 3D illustration of the proposed slotted fishbone structure. Optical mode conversion from the strip to the slot region is achieved through the taper mechanism, as previously reported in [7]. Inset shows the electric-field distribution of wave propagation in the proposed structure. (b) Optical transmission characteristics of the proposed sensor are shown across varying wavelengths. (c) Calculated group index as a function of wavelength, attributed to the slow-light feature of the proposed sensor.

The proposed design of the slotted fishbone structure is illustrated in Fig. 1(a). The device is based on a silicon-on-insulator (SOI) platform, consisting of a 220 nm thick silicon device layer and a 2 µm thick SiO_2 layer. The design optimization aims to achieve a low group velocity while ensuring strong optical confinement in the cladding region. The plane wave expansion (PWE) method, implemented using the RSOFT tool, is employed to analyze the band diagram, following a methodology similar to that in previous studies [5]. Particular attention is given to the flattened bands in the edge regions of the band diagram, as these correspond to modes with a high group index.

The optimized parameters for the grating period, duty cycle, and slot width are determined to be 0.41 µm, 47%, and 120 nm, respectively. The structure is fully etched and requires only a single mask for fabrication, simplifying the manufacturing process. Subsequently, the 3D finite-difference time-domain (FDTD) method is used to evaluate the optical properties of the structure. To enhance optical transmission, a tapered group index scheme [8] has been implemented, effectively mitigating back reflections and coupling inefficiencies. The optical transmission spectrum, shown in Fig. 1(b), demonstrates a wide transmission window that spans the entire C-band (1530–1565 nm). As depicted in Fig. 1(c), the group index is plotted as a function of wavelength, revealing a slow-light feature over a range of wavelengths. This indicates that the structure is robust against fabrication-induced variations. The optimized structure exhibits a high optical confinement factor of 40% in the analyte region, leading to 27 times greater light-analyte interaction ($\Gamma_{air} \times n_g$) compared to free space, assuming the same interaction length. These characteristics highlight the structure's potential for highly sensitive on-chip sensing applications. The authors gratefully acknowledge support from the Department of Energy (DOE) under contract number DE-SC0023917.

3. References

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