Large Free Spectral Range Optical Filtering with Engineered Multi-Mode Asymmetric Grating

Sourabh Jain[1, *], Niraj Kumar[2], Mukesh Kumar[3] and Ray T Chen[1,4,]

[1]Department of Electrical and Computer Engineering, University of Texas at Austin, TX 78758, USA
[2]Department of Chemistry, Inha University, Incheon, 100 Inha-ro, Michuhol-gu, Incheon, South Korea
[3]Department of Electrical Engineering, Indian Institute of Technology, Indore-453552, India
[4]Omega Optics, Inc., 8500 Shoal Creek Blvd., Bldg. 4, Suite 200, Austin, Texas 78757, USA
[*]Author e-mail address: sourabhjain@utexas.edu

Abstract: A compact 1D-asymmetric silicon photonic-crystal is designed for a significantly large free-spectral-range via intermodal interference. The device demonstrates efficient optical filtering, boasting a substantial extinction ratio of 20dB and a moderate group index of 15.

1. Introduction

Optical filters are essential components in on-chip photonic systems, facilitating various applications in communication, spectroscopy, bio-sensing, computing, and high-precision measurement. Filters with an broad free spectral range (FSR) are particularly important for accessing multiple wavelength channels necessary for optical transmission and multipoint sensing [1]. Wavelength-division-multiplexing (WDM) technology relies on optical filters as fundamental components for (de)multiplexing, allowing flexible filtering and combining of signals in optical communication. WDM also enables the deployment of sensor networks for quasi-distributed multisite and multiparameter sensing. The current method for on-chip filtering faces several challenges such as limited FSR, poor fabrication tolerance, and high dependency on external variations like temperature. Crucial to integrated photonics, a filter with an ultrawide FSR and device miniaturization is indispensable for enhancing the number of multiplexed channels and facilitating concurrent sensing applications. Various on-chip optical sensors, including Micro Ring Resonators (MRRs), Interferometry structures, Sub-Wavelength Grating (SWG) structures, and 1D and 2D photonic crystal-based sensors, have been developed [2-5]. Each has its advantages and limitations. For instance, MRR-based sensors offer a high-quality factor (Q) but suffer from high-temperature dependency and small FSR. Mach Zehnder Interferometer (MZI) based sensors provide wide operational bandwidth but require a larger footprint. Contra-directional couplers (CDCs) are developed leveraging the photonic bandgap property of Bragg gratings. However, due to the disproportionate bandwidth-to-length ratio of Bragg gratings, devices incorporating shallow gratings might require excessive length. To address this, CDCs coupled with the MRRs to attain a notable resonance, effectively reducing the size of filters. Maximum side-mode suppression ratio at unwanted spectral wavelengths is ensured when the stopband of the grating is two times that of MRR's FSR. Alternative approach involves applying the Vernier effect, cascading multiple MRRs with different FSRs to achieve a larger FSR [6]. However, achieving resonant wavelength alignment is challenging due to the stringent requirements for design and fabrication accuracy. Unlike Si-based MRRs and MZI structures, SWG-based structures offer controllable properties, allowing desirable optical characteristics. However, conventional grating structures face challenges such as the need for millimeter-long devices and high-temperature dependency. Recent advancements in asymmetrical Bragg gratings on silicon show promise but still suffer from narrow FSR limitations.

Previously, we have reported novel filtering characteristics utilizing asymmetric multimode grating waveguides in the silicon platform [7]. We demonstrated a one-dimensional photonic crystal consisting of two distinct grating periods on each side of the cavity section which enables the realization of only one transmission resonance spectrum with a notable extinction ratio of >18dB. The filter design is fine-tuned to ensure the simultaneous propagation of the fundamental TE mode (TE_0) and 1st-order TE mode (TE_1) in the fully etched comb like gratings, creating two separate rejection windows centered at distinct positions based on their respective effective refractive indices (n_{eff}). Within a small physical footprint of just 18 µm², the proposed filter design allows for a single transmission resonance of 1.8 nm FWHM. In this work, we expand our investigation to examine the slow-light characteristics of the previously identified large FSR-attributed resonating mode within the waveguide. The numerical analysis indicates a moderate group index (n_g) for the resonating mode, along with a large FSR nature using the proposed methodology. The presence of fully etched gratings in the vertical direction and partially etched in lateral direction (to achieve structural asymmetricity) with such slow light behavior facilitates strong light-analyte interaction.

2. Device Design, Working and Measurement

The device optimization and working principle is similar to our previous study [7]. The device's 3D schematic is shown in Fig.1(a) and Fig. 1(b) shows SEM image of the fabricated device. The structure comprises dual sets of SWGs with distinct periods, which are isolated by a cavity section. The gratings

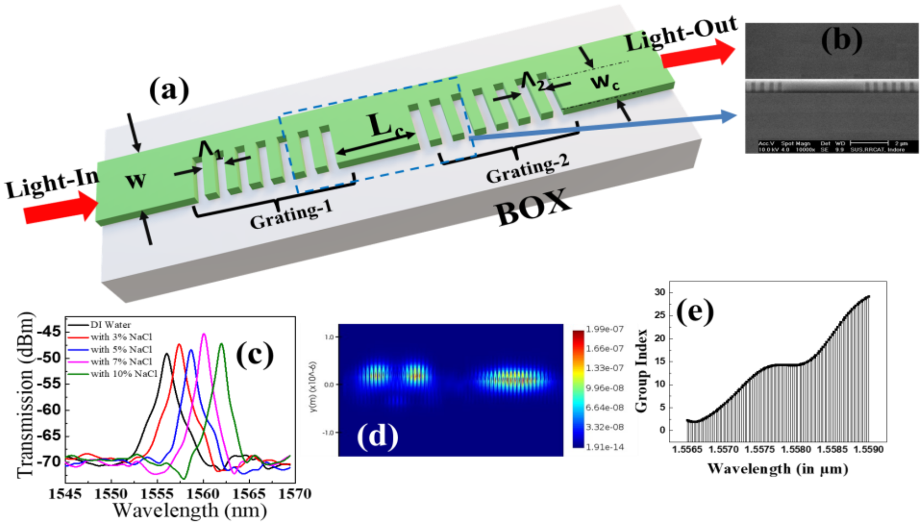

Fig. 1; (a) Illustration of the filter designed on an SOI wafer, with a blue arrow indicating an electron microscopic image of the gratings and cavity section in (b). (c) The experimental findings illustrate the optical properties of the filter, involving the testing of a varying upper cladding consisting of distinct concentration of NaCl solution in De-Ionized water. A noticeable resonance shift of approximately 6 nm is observed when the NaCl concentration varies from 0% to 10% [7]. (d) Simulation result depicting the electric field distribution at the resonant wavelength in the waveguide. (e) Simulated n_g considering resonating wavelength at 1558nm.

have periods and duty cycles of 0.38 µm, 0.386 µm, and 55%, respectively. The grating width and corrugation width are 0.75 µm and 0.565 µm, respectively. The device width is intentionally designed to accommodate TE_0 and TE_1. The coupling of these modes with the individual sets of SWGs leads to interaction between different modes in both the forward and backward propagation directions, contributing to the overall behavior of the system. Two optimized multimode gratings support two band rejection windows separated by a passband window, forming a single transmission spectrum. These resonant transmission spectra shift based on the n_{eff} of the propagating modes. Following this, we conducted an analysis of the optical characteristics across various concentrations of NaCl solutions at a temperature of 300K. In Fig. 1 (c), a resonance shift of the transmission peak is observed with varying NaCl concentration. The calculated change in refractive index with NaCl concentration exhibits a device sensitivity of 0.352 µm/RIU. Fig. 1(d) shows the electric field distribution of the resonating mode within the waveguide. The extended corrugation width of the gratings is evident in the illustration, leading to the expansion of the mode into the cladding region. This extension facilitates enhanced interaction of light with the analyte present in the cladding. Theoretical calculations of the group index of the propagating mode, as presented in Fig. 1(e), reveal a slow-light behavior of approximately 15, which is nearly four times more effective than the unperturbed silicon waveguide. In summary, the suggested device structure relies on the coupling between the fundamental and higher-order leaky mode where tuned resonance between two sets of grating isolated by cavity section leads to slow light behavior and facilitate a robust interaction between light and the analyte within the cladding. This proposed comb-like optical device offers a method to realize a compact on-chip filter with a significantly large FSR, suitable for diverse applications in integrated photonics.

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