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Controlling the propagation of light and sound in silicon waveguides by means of subwavelength nanostructuring

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Abstract

Periodically patterning silicon with a pitch sufficiently small to suppress diffraction effects opens new degrees of freedom to control light propagation in silicon photonic circuits with unprecedented flexibility. Concurrently, near-infrared photons and GHz phonons in nanoscale Si waveguides have comparable wavelengths. Thus, subwavelength nanostructuring has a great potential to shape light-sound interactions in silicon waveguides. Here, we present our most recent results on the subwavelength engineering of silicon for the implementation of high-performance photonic and optomechanical components.

1. Introduction

Periodically patterning silicon with a pitch sufficiently small to suppress diffraction effects opens new degrees of freedom to control light propagation in silicon photonic circuits with unprecedented flexibility [1-3]. Indeed, this subwavelength metamaterial concept has enabled the demonstration of several Si photonic components, some with the best performance ever reported [2,3]. On the other hand, near-infrared photons and GHz phonons in nanoscale Si waveguides have comparable wavelengths (around 1 μm) [4,5]. Thus, subwavelength nanostructuring of silicon has a great potential to shape the properties (confinement, dispersion, etc.) of both, photonic and phononic modes, thereby opening new routes to engineer light-sound interactions in silicon, e.g. Brillouin scattering. Here, we present our most recent results on the subwavelength engineering of silicon for the implementation of high-performance photonic and optomechanical components.

2. Spectral filters

Bragg optical filters are widely used in photonics for advanced on-chip signal manipulation. However, achieving narrowband Bragg filters with large rejection levels is often hindered by fabrication constraints and imperfections. We have developed a new generation of high-performance Bragg filters that exploit subwavelength grating (SWG) and symmetry engineering to overcome this bandwidth-rejection trade-off. We experimentally show flexible control over the width and depth of the Bragg resonance [6]. We have also developed a novel approach that leverages non-coherent cascading of multi-modal waveguide Bragg gratings to achieve ultra-high rejection levels, exceeding 80 dB [7]. The proposed architecture comprises several filter sections implemented with Bragg gratings that couple back-reflections into a high-order waveguide mode. These sections are connected by single-mode waveguides that radiate back-reflections propagating in a high-order mode. This configuration avoids any coherent interaction among filters, enabling efficient cascading even in the presence of phase errors. These results pave the way for the implementation of high-performance on-chip pump-rejection filters with a great potential for Si-based quantum photonic circuits.

3. Optomechanical silicon waveguides exploiting subwavelength engineering

Brillouin scattering is a third order optical nonlinear process that results from light-sound coupling that has been widely exploited fiber optics. The availability of materials co-confining phonons and photons in the same photonic device is fueling the study of Brillouin interaction on chip [10,11]. Recent demonstrations have shown Brillouin interactions in

silicon chips with strengths that surpassed those of Kerr and Raman effects [4,5]. Acoustic phonons with GHz frequencies and near infrared photons in nanometric-scale silicon waveguides have very similar wavelengths, enabling high-efficiency coupling that resulted in the demonstration of remarkably large Brillouin gain [4] and even Brillouin lasing [5]. Silicon membranes are an appealing solution to efficiently confine photons and phonons [5,12]. Still, efficient Brillouin interactions in Si membranes are hampered by acoustic leakage, due to coupling to the lateral silicon slabs. This loss has been alleviated by inserting air gaps [5] or by implementing phononic stop bands in the transversal dimension [12]. However, the efficiency of these approaches is limited by weak photon-phonon overlap or narrowband operation. Here, we present a new waveguide geometry that harnesses geometrical subwavelength softening to minimize the loss of acoustic modes and subwavelength index engineering to confine optical modes. The proposed subwavelength-lattice waveguide, that works well below the photonic and phononic bandgaps, provides simultaneous enhancement of the quality factor of the acoustic mode and the photon-phonon interaction. Our calculations predict a remarkably large Brillouin gain exceeding $10000 \text{ (W}\cdot\text{m)}^{-1}$. These results open exciting prospects to achieve up to a three-fold improvement in Brillouin gain, compared to previous demonstrations [4,5,13].

4. Conclusions

In conclusion, we exploit the subwavelength nanostructuring of Si photonic waveguides to demonstrate a new generation of high-performance Bragg grating filters. In addition, we present a new approach to optimize Brillouin scattering in silicon optomechanic waveguides, based on subwavelength engineering of light and sound. The proposed optomechanic waveguide relies upon a silicon membrane with a subwavelength-lattice structuration to optimize the photon-phonon interaction and the acoustic quality factor, simultaneously. Our calculations predict that the proposed waveguide may provide high acoustic quality factor up to 2000 and Brillouin gain up to $10000 \text{ (W}\cdot\text{m)}^{-1}$. We believe these results open a new route to engineer photon-phonon interactions exploiting subwavelength-lattice structuration in silicon opto-mechanic waveguides.

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