Degenerate band edge resonances in periodic silicon ridge waveguides

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We experimentally demonstrate degenerate band edge resonances in periodic Si ridge waveguides that are compatible with carrier injection modulation for active electro-optical devices. The resonant cavities are designed using a combination of the plane-wave expansion method and the finite difference time domain technique. Measured and simulated quality factors of the first band edge resonances scale to the fifth power of the number of periods. Quality factor scaling is determined to be limited by fabrication imperfections. Compared to resonators based on a regular transmission band edge, degenerate band edge devices can achieve significantly larger quality factors in the same number of periods. Applications include compact electro-optical switches, modulators, and sensors that benefit from high-quality factors and large distributed electric fields. © 2015 Optical Society of America

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Periodic dielectric waveguides with one-dimensional periodicity provide many of the properties found in structures with higher-dimensional periodicity but with reduced fabrication complexity [1–3]. Ridge waveguides with periodicity allow for the fabrication of carrier injection devices where dopants can be placed close to a resonant cavity, reducing electrical power consumption of switches, modulators, and active sensors [4–10]. Furthermore, dispersion engineering can be used to reduce group velocity, increasing light–matter interaction for nonlinear optics [11,12] and lasing [13].

Resonators based on periodic dielectric waveguides can be realized by introducing a defect in the periodicity or by truncating periodicity to a finite number of periods. In defect-based resonators, a resonance is created inside the photonic bandgap [1,2,4–8]. In this Letter, the focus is on finite-length periodic structures where resonances are exploited near the photonic band edge [9,13–15]. Finite-length periodic structures consisting of a single grating have a quadratic dispersion relationship near the band edge given by \( \omega - \omega_0 \propto (k - k_0)^2 \) where \( \omega \) is the frequency, \( k \) is the wave number, and \( \omega_0 \) and \( k_0 \) are the corresponding values at the band edge. Quadratic dispersion gives rise to a regular band edge (RBE) resonance and quality factor (Q) scaling proportional to \( N^2 \), where \( N \) is the number of periods [16,17]. In contrast, when the band edge resonator consists of two coupled periodic gratings, it is possible to engineer a quartic dispersion relationship near the band edge \( \omega - \omega_0 \propto (k - k_0)^4 \), giving rise to degenerate band edge (DBE) resonances [18]. On a DBE resonance, the light intensity inside the cavity forms a giant slow wave resonance whose maximum amplitude scales as \( N^4 \) [16,17]. The quality factor scaling of DBE resonances is proportional to \( N^5 \) [17]. In addition, DBE resonances can demonstrate near-unity transmission on resonance from the presence of propagating and evanescent cavity modes [15,17,19]. Devices based on DBE resonances have applications in low-threshold all-optical switching [20] and lasing [21].

Initial theoretical studies of DBE resonances were based on one-dimensional periodic layered structures with strong birefringence [16] or optical fibers with multiple gratings [19,22]. Recently, finite-length coupled periodic integrated optical waveguides have been studied as a more practical and physically realizable platform for on-chip devices based on DBE resonances [14,18]. Although coupled periodic strip waveguides have been shown to demonstrate DBE resonances both theoretically [18,23] and experimentally [14], there has not yet been a report of DBE resonances in ridge waveguides required for carrier injection.

In this work, we design, fabricate, and experimentally demonstrate resonators that exhibit DBE resonances and are compatible with carrier injection through a cavity design that includes a 40 nm Si slab for ion implantation of dopants. We present a design methodology for obtaining a DBE resonance along with details of the fabrication process. The resonators are promising candidates for compact devices due to fifth-order Q scaling with the number of periods. The peak measured quality factor in demonstrated devices is 16,700, limited by fabrication imperfections.

A schematic of the ridge waveguide cavity designed for a DBE resonance is shown in Fig. 1. The resonator consists of a 790 nm wide Si waveguide, \( w \), with a one-dimensional array of pairs of etched holes with a period, \( a \), of 370 nm. The ridge waveguide is partially etched from a height of 205 nm to leave a 40 nm Si slab, \( s_h \), external to the cavity. Two 395 nm wide input and output Si ridge waveguides are used to couple light into and out of the cavity. A multimode ridge waveguide region of length \( z_L \) is included between the Y-junctions of the input and output waveguides and the cavity to allow excitation of the cavity modes with light input only on port 1 and output primarily on port 4 [14].

To arrive at a design for the periodic region, the impact of changes in the hole radius (\( r \)), longitudinal offset (\( z_0 \)), and lateral offset (\( x_0 \)) on the band diagram are simulated by the three-dimensional plane-wave expansion method [24,25]. We use a refractive index of 3.48 for the silicon ridge, 1.41 for the spin-on glass (FOX-15), and 1.45 for the buried oxide (BOX) and plasma-enhanced chemical vapor deposition (PECVD) SiO\(_2\) claddings surrounding the ridge. The design methodology is presented in

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Fig. 1. Schematic of the resonant cavity designed to exhibit a DBE resonance in a ridge waveguide. (a) Top view of the complete cavity; (b) top view of the coupling region; (c) cross-sectional view. The oxide top cladding is not shown in (a) and (b) for clarity.

Fig. 2. First, as shown in Fig. 2(a), the hole radius and lateral offset are swept for a fixed longitudinal offset of 0 nm to maximize the size of the bandgap between the second (red) and third (green) quasi-TE modes (dominant electric field component $E_{xy}$) and to position the peak of the second band near the design frequency. Next, as shown in Fig. 2(b), the longitudinal offset is increased until the second band takes on the desired quartic form. As shown in Fig. 2(c), continuing to increase the longitudinal offset results in a split band edge (SBE) in which the band diagram is no longer quartic and the group velocity reaches zero away from the band edge [23,26].

The quartic dispersion relationship and $N^5 Q$ scaling corresponding to a DBE resonance occur only in a small parameter space with significant deviation resulting in either an RBE or SBE resonance. Once the periodic region is designed, finite-difference time-domain (FDTD) simulations (Lumerical FDTD, Vancouver, Canada) are performed on finite-length periodic structures to confirm that the $Q$ of the first resonances scales to the fifth power with an increasing number of periods. FDTD results are presented alongside measurements. Additional FDTD simulations are used to design $z_L$ so that the input port 1 to output port 4 transmission is maximized at the first resonance. Length $z_L$ is set to the same value on both sides of the periodic structure. The final design parameters are $w = 790$ nm, $h = 165$ nm, $s_b = 40$ nm, $s_w = 20$ μm, $a = 370$ nm, $r = 130$ nm, $z_0 = 115$ nm, $x_0 = 380$ nm, and $z_L = 750$ nm.

The devices are fabricated on a silicon-on-insulator wafer with a silicon device layer of 210 nm and BOX thickness of 1 μm. Electron beam lithography (EBL) is used to pattern waveguides and alignment markers with a hydrogen silsesquioxane (HSQ) mask [27]. Ridge waveguides are patterned with inductively coupled plasma reactive ion etching (ICP-RIE) with a Cl$_2$/O$_2$ chemistry, leaving a 60 nm Si slab.

Next, EBL is used with negative-tone maN-2403 resist to pattern the Si slab. The maN-2403 mask is 20 μm wide around the DBE cavity and 3 μm wide around the input and output waveguides. The maN-2403 is not exposed directly above the DBE cavity to allow etching of the holes to the BOX layer. The HSQ serves as an etch mask for the Si ridge. The Si slab width is tapered to connect the slab surrounding the cavity to the input and output waveguides. Strip waveguides are needed for fiber-to-chip coupling with cantilever couplers [28,29]. ICP-RIE with Cl$_2$/O$_2$ is used to completely etch the Si slab outside of the patterned regions. Images of fabricated devices after the slab patterning etch are given in Fig. 3. Patterning the slab layer electrically isolates nearby devices [30].

Dry thermal oxidation is then performed to reduce the sidewall roughness, decreasing propagation loss [31]. Approximately 20 nm of Si is consumed in both slab regions and along the sidewalls. Oxidation is slower in the vertical dimension in the ridge waveguide, since residual 50 nm HSQ on top of the Si core acts as a partial oxidation mask. The top cladding consists of FOX-15 and PECVD SiO$_2$ [14]. The FOX-15 is used to completely fill the periodic holes without leaving air voids. After spin coating, the FOX-15 is baked for 1 h in a $N_2$ ambient
at 400°C, resulting in a film thickness of 545 nm. PECVD SiO$_2$ is then deposited to give a total oxide cladding thickness of 1 μm. Finally, compact cantilever couplers are patterned for low-loss fiber-to-chip coupling.

Devices are characterized by optical transmission measurements. Linearly polarized TE light from an IR tunable laser source (1460–1580 nm) is coupled into the device via a single-mode tapered fiber butt coupled to a compact cantilever coupler on port 1. Output light is coupled from port 4 to another tapered single-mode fiber and measured with a photodetector and power meter. Ports 2 and 3 are terminated with inverse width tapered waveguides but are not released from the substrate with cantilever couplers like ports 1 and 4. Any light scattered to ports 2 and 3 is radiated into the oxide cladding away from the cavity and is not collected by the input or output tapered fibers. Figures 4(a) and 4(b) present the measurement results for devices with 30 and 40 periods, respectively, along with Fano resonance fitting [14,32]. Q scaling of the first resonance, closest to the bandgap, for both measured (blue) and simulated (red) devices is shown in Fig. 4(c). In both cases, Q scales proportional to $N^5$ for $N > 20$, which is a defining characteristic of a DBE resonance with two propagating and two evanescent modes [17,18]. While the simulated Q continues scaling for an increasing number of periods, measured Q drops off of $N^5$ scaling after 40 periods or a Q of 13,000. The peak measured Q of 16,700 occurs for 50 periods.

To understand why Q stops increasing after 40 periods, we use the model established in [33], in which fabrication imperfections such as nonuniform hole radius, sloped sidewalls, and roughness of the Si slab are described by a quality factor, $Q_{\text{Imperfections}}$, as

$$Q_{\text{Exp}}^{-1} = Q_{\text{Design}}^{-1} + Q_{\text{Imperfections}}^{-1},$$

where $Q_{\text{Exp}}$ is the experimental measurement and $Q_{\text{Design}}$ is obtained from FDTD modeling. The filter-diagonalization method for harmonic inversion is used to extract $Q_{\text{Design}}$ from FDTD simulations of the cavity with excitation from a broadband (1.3–1.7 μm) source [34,35]. The quality factors from Eq. (1) are plotted in Fig. 5. The $Q_{\text{Imperfections}}$ term shows no clear trend with $N$, and its average value, 17,200, is close to the peak of $Q_{\text{Exp}}$. Fifth-power Q scaling of $Q_{\text{Exp}}$ stops as the measured values approach $Q_{\text{Imperfections}}$.

Based on SEM inspection of the etched holes and the analysis of fabricated devices in [33,36,37], we expect

![Fig. 3. Images of fabricated ridge waveguide DBE devices: (a) optical micrograph; (b) angled-view scanning electron microscope (SEM) micrograph of the cavity region. Insets: left, zoom-in top-down SEM micrograph of the periodic ridge waveguide; right, angled-view cross-section SEM of a Si companion sample cleaved along the dashed line in the left inset.](image)

Fig. 4. Measurement results: transmission spectra for devices with (a) 30 and (b) 40 periods, with an optical power of 0 dBm at the chip input facet. A constant term has been added to the sum of Fano fits to match the finite reflectivity measured in the bandgap. (c) Quality factor scaling of the first resonance peak on the long wavelength side of the photonic bandgap.

![Fig. 5. Analysis of measured quality factor and impact of fabrication imperfections as a limitation.](image)
that the largest contributions to $Q_{\text{imperfections}}$ are variation in the hole radius, sidewall roughness, and the slope of the hole sidewalls. Improvements to fabrication processes of photonic crystal slabs with two-dimensional periodicity have demonstrated an increase in $Q_{\text{imperfections}}$ and a corresponding increase in $Q_{\text{Exp}}$.\textsuperscript{[39]} Theoretical studies have also shown that DBE resonances are more sensitive to fabrication imperfections than RBE resonances.\textsuperscript{[39]} The design of future active ridge waveguide DBE resonators based on carrier injection modulation must also account for the changing complex refractive index with the density of injected carriers. Significant changes to the Si refractive index will alter the dispersion relationship from the target quartic form of the DBE. Modifications of the initial cavity design could potentially be used to give quartic dispersion when under bias.

In summary, we have designed and experimentally demonstrated DBE resonances in periodic Si ridge waveguides. The $N^5Q$ scaling of these resonances is enabling for future compact electro-optic devices. We expect that improvements to the fabrication process will lead to higher absolute $Q$, since devices are currently limited by fabrication imperfections rather than a fundamental limit of the design. Electro-optically active DBE resonances have applications in low-power-consumption modulators, distributed area sensors, and on-chip light emitters.

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References


