Strong polarization mode coupling in microresonators

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We observe strong modal coupling between the TE_{00} and TM_{00} modes in Si$_3$N$_4$ ring resonators revealed by avoided crossings of the corresponding resonances. Such couplings result in significant shifts of the resonance frequencies over a wide range around the crossing points. This leads to an effective dispersion that is one order of magnitude larger than the intrinsic dispersion and creates broad windows of anomalous dispersion. We also observe the changes to frequency comb spectra generated in Si$_3$N$_4$ microresonators due to polarization mode and higher-order mode crossings and suggest approaches to avoid these effects. Alternatively, such polarization mode-crossings can be used as a novel tool for dispersion engineering in microresonators.

Optical microresonators are important for a wide range of applications, such as parametric frequency combs [1-10], optomechanics [11,12], and in quantum optics as sources for photon-pairs [13-19] or squeezed states [20-21]. The microresonator resonances can in principle be precisely calculated using the dispersion of the resonating modes and the resonator length. However, modal coupling between different types of modes can significantly alter the shape and position of their resonances. Mode splitting occurs for strong coupling [22], and coupling between whole families of modes results in avoided crossings [23-27]. This can lead to dramatic localized changes in the effective dispersion near these crossing points, which in general affects any parametric interaction that relies on precise frequency matching of different resonances. In particular it can play an important role in the formation of parametric frequency combs [24-31]. While mode-crossings can be disruptive for comb generation by inhibiting soliton formation [25] and distorting the comb spectrum [27], they can also be beneficial, allowing for comb formation in resonators with normal group-velocity dispersion (GVD) [8,24] or aiding the generation of dark solitons in normal GVD resonators [29]. In the context of frequency comb generation, only modal interactions between different families of spatial modes have been considered thus far. However, in dielectric waveguides, even when the waveguide is 'single mode', there are typically at least two guided fundamental modes, the fundamental quasi transverse electric (TE$_{00}$) and the fundamental quasi transverse magnetic (TM$_{00}$) mode, which correspond approximately to the polarization of light in the waveguide.

Here, we report on the observation of avoided crossings that result from the strong modal coupling between the TE$_{00}$ and TM$_{00}$ polarization modes in Si$_3$N$_4$ microring resonators. Similarly, strong polarization mode coupling has been shown to be useful for polarization conversion based on silicon oxinitride technology [31]. Since such a mode interaction can even occur in single-mode waveguides, it is more fundamental than other forms of modal interactions (i.e., between higher-order spatial modes). The physical origin and strength of the modal coupling between the TE$_{00}$ and TM$_{00}$ modes are based on different parameters of the ring resonator such as its radius of curvature, waveguide cross-section, and side-wall angle [32,33]. Microresonators with smaller radii and larger side-wall angles typically will exhibit greater modal coupling.

Our experimental setup for investigating polarization mode coupling is depicted in Fig. 1. We probe the resonators with two different external-cavity diode lasers covering a total tuning range between 1450 nm and 1640 nm. Lensed fibers are used to couple into and out of the bus waveguide with inverted tapers [34] for mode-matching. The polarization of the input and output light is controlled and analyzed with standard fiber-based polarization controllers and a polarization beam splitter, and the output power is monitored with a sensitive photodiode. We use a temperature controller with a Peltier element on the chip holder to stabilize and tune the Si$_3$N$_4$ microring resonators under investigation. To overcome the limited precision of our tunable lasers, we use an automated stepped scanning and fitting routine supplemented by calibrating each resonance position with a high-precision wavemeter. We find that this method leads to an average precision better than 50 MHz.

Fig. 1. Schematic of the setup used for observing and characterizing polarization mode coupling in microresonators on a temperature stabilized (T) silicon chip.
We first investigate polarization mode coupling in two Si$_3$N$_4$ microrings with 725×1100 nm$^2$ and 725×900 nm$^2$ waveguide cross-section and a 100 µm radius. The transmission measurement for TM$_{00}$ input light for the first microring (Fig. 2) yields sharp and deep resonances due to nearly critical coupling between the bus waveguide and the resonator. Near 1595 nm a second sharp resonance, which we associate with the TE$_{00}$ mode, appears on the right side of the main TM$_{00}$ resonance and becomes deeper until both show the same extinction. The main resonance then experiences an adiabatic crossover and the secondary resonance (now on the left side) slowly disappears. We attribute this behavior to an avoided crossing at 1595 nm associated with a strong modal interaction between the TE$_{00}$ and TM$_{00}$ modes.

To observe the avoided crossing associated with the strong polarization mode coupling, we next precisely measured the resonance wavelengths for both the TE$_{00}$ and TM$_{00}$ polarizations as shown in Fig. 3. For the first microring the measured free spectral ranges (FSR’s) at the start of the scan (1510 nm) are 225.0 GHz and 226.3 GHz for the TM$_{00}$ and TE$_{00}$ modes, respectively. This agrees very well with the FSR’s calculated from the simulated dispersion based on a finite-element mode-solver [also shown in Fig. 2(b)] and therefore further corroborates the identification of the modes as TM$_{00}$ and TE$_{00}$. As shown in Fig. 3(a) a strong avoided crossing occurs near 1595 nm with the upper branch (blue) changing its mode character continuously from TE$_{00}$ to TM$_{00}$, and vice versa for the second branch. We find a similarly strong avoided crossing for the microring with a 725×900 nm$^2$ waveguide cross-section [Fig. 3(d)]. The splittings of the modes at the anti-crossings is 7.2 GHz and 12.5 GHz, respectively. For both resonators this is around 20 times larger than their intrinsic loss rates, which we measure to be 340 MHz ($Q_{\text{int}} = 600,000$) and 700 MHz ($Q_{\text{int}} = 300,000$), respectively, and shows that for both microrings the TE$_{00}$ and TM$_{00}$ modes are strongly coupled.

As shown in Fig. 3(b) and 3(e), near the crossing points, the measured FSR’s deviate significantly from their values given by the dispersion and resonator length. This can be interpreted as a mode-coupling induced effective dispersion [8]. By fitting the FSR’s for the different branches and taking the derivatives of these fits the values of this
effective GVD can be directly determined from the measured data [Fig. 3(c),(f)]. For the first microring we observe relatively high values of the effective GVD reaching around +600 ps/nm/km and -900 ps/nm/km, respectively. Moreover, for the TE_{00} branch (that turns into TM_{00} after the crossing) there is a wide range between 1550 nm and 1610 nm of anomalous GVD. We measure a similar effect on the effective GVD in the second microring [Fig 3(f)] with an anomalous GVD region between 1450 nm and 1495 nm.

We further investigate the effects of both polarization and higher-order mode crossings on comb generation by directly comparing the comb spectra generated in microring resonators with a measurement of its mode-crossings (Fig. 4). The combs are generated by strongly pumping a single resonance at 1540 nm [4]. We investigate a microring resonator with a waveguide cross-section of 725×1650 nm^2 and a 100-µm radius [Fig. 4(a)]. We observe a polarization mode-crossing near 1580 nm with a splitting at the avoided crossing of 2.2 GHz, which greatly exceeds the intrinsic loss rate of the resonator. This polarization mode crossing manifests as a reduction in the mode intensity in the generated comb spectrum. In addition, there exists an anomaly in the FSR at 1550 nm, which can be attributed to a mode crossing at a higher-order spatial mode, and we observe a similar corresponding feature in the comb spectrum. Furthermore, we observe suppressed comb generation when pumping near one of the higher order mode crossings which we attribute to the large change in the effective dispersion. Since this effect can be disadvantageous for applications related to frequency comb generation, it needs to be taken into account in the optimal device design. Moreover, we investigate the effects of mode crossings on comb generation in an 80-GHz FSR microresonator with a waveguide cross-section of 725×1700 nm^2 and 1.8-mm length [Fig. 4(b)]. For this microresonator our measurements reveal three polarization mode crossings and a number of higher-order mode crossings that affect the comb spectrum generated from this resonator.

We identify different strategies that could minimize the disruptive effects of mode-crossings (polarization and higher-order mode) on frequency comb generation. In general, mode-crossings are especially disruptive when they appear directly at the pump wavelength or when they line up symmetrically with respect to the pump since they will then simultaneously affect both the signal and idler resonances. Since the position of any mode-crossing depends sensitively on the exact length of the microresonators, slight variations in the design of the resonator lengths can be used to circumvent both scenarios. In addition, if the target application allows it, increasing the FSR will reduce the frequency at which mode-crossings will occur. Another approach for reducing mode-crossing disruptions would be to minimize the modal interactions altogether, which may be achieved by optimizing the microresonator design and fabrication, including larger bend radii or smaller side-wall angles. Furthermore, we have observed experimentally that higher-order mode-crossing are suppressed for the narrower and thus more symmetric cross-section resonators (Fig. 3) as compared to the wider, more asymmetric cross-section resonators (Fig. 4). This indicates that the aspect ratio can be used as an additional parameter for controlling mode-crossing effects.

In summary, we observe and characterize strong avoided crossings between the TE_{00} and TM_{00} mode by revealing the mode crossings. (a) Results for a 725×1650 nm^2 cross-section, 100-µm radius microring resonator. A polarization mode crossing (pol) occurs near 1580 nm with a corresponding feature (indicated by an arrow) in the comb spectrum. A second anomaly in the FSR near 1550 nm due to a mode crossing with a higher order spatial mode (hom), also produces a corresponding feature in the spectrum. (b) Results for a 725×1700 nm^2 cross-section, 1.8-mm length microresonator. A number of polarization and higher-order mode crossings affect the generated comb spectrum.

![Generated comb spectra in SiN resonators](image)
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