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Vincent Ng, Noel Lito B. Sayson, Luke S. Trainor, Harald G. L. Schwefel, Stéphane Coen, Miro Erkintalo, Stuart G. Murdoch, "Broadly tunable light sources using four-wave mixing in magnesium fluouride microresonators," Proc. SPIE 11200, AOS Australian Conference on Optical Fibre Technology (ACOFT) and Australian Conference on Optics, Lasers, and Spectroscopy (ACOLS) 2019, 112001I (30 December 2019); doi: 10.1117/12.2539873

Event: ANZCOP, 2019, Melbourne, Australia

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Through their small modal volumes and ultra-high finesse, optical microresonators are capable of exhibiting rich nonlinear behaviour, driven by pump powers in the milliwatt range.[1] Microresonators with Kerr type nonlinearities have been the focus of much research, resulting in the demonstration of chip-scale coherent optical frequency combs, underpinned by four-wave-mixing.[2] Here, we consider a four-wave-mixing process in microresonators which generates widely-separated parametric sidebands, symmetrically spaced around the pump.[3,4] These sidebands can be generated more than an octave apart, and can be tuned quasi-continuously over this range. These widely separated sidebands are permitted by higher-order dispersion, requiring require normal (positive) second-order dispersion β_2 and anomalous (negative) fourth-order dispersion β_4. Previously, an experimental study of widely-tunable parametric sidebands in silica microspheres was carried out.[5] However, the maximum tuning range in silica was limited by material absorption at wavelengths longer than 1900 nm. Furthermore, the broad Raman gain bandwidth in silica resulted in the generation of undesirable frequencies.

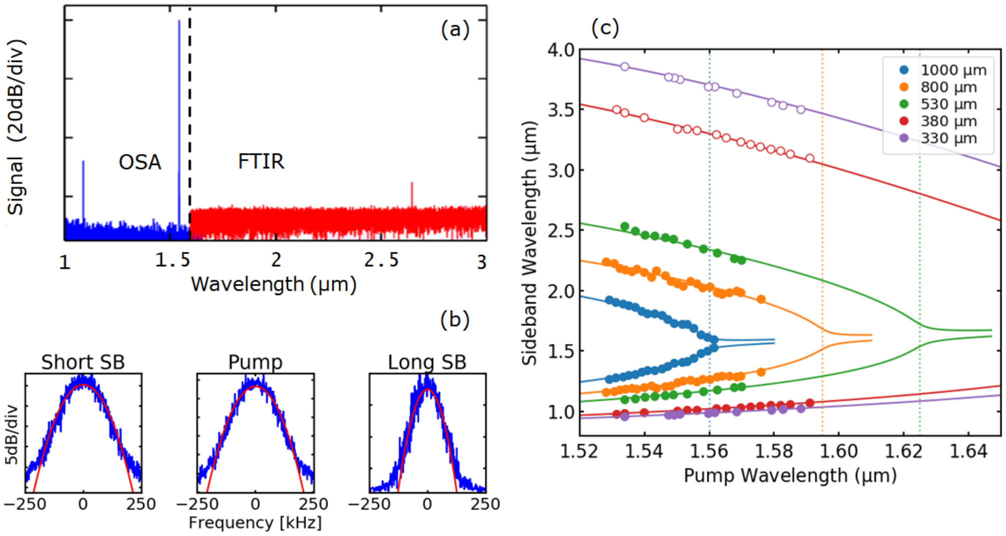

Figure 1. (a) Spectra of widely spaced sidebands. The pump and the short wavelength sideband were measured using an OSA, while the long wavelength sideband was measured using a FTIR spectrometer. (b) Phase-matching curves for the microresonators. Dotted lines indicate the ZDW. Directly measurements are shown as solid markers, whereas sidebands inferred from the short sideband wavelength are open markers. The 3380 and 380 μm resonators were additionally probed with an L-band laser. (c) Linewidth measurements, using a self-heterodyne technique.

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AOS Australian Conference on Optical Fibre Technology (ACOFT) and Australian Conference on Optics,
Lasers, and Spectroscopy (ACOLS) 2019, edited by Arnan Mitchell, Halina Rubinsztein-Dunlop, Proc. of SPIE
Vol. 11200, 112001I · © 2019 SPIE · CCC code: 0277-786X/19/$21 · doi: 10.1117/12.2539873

Here, we fabricated microresonators out of magnesium fluoride. Magnesium fluoride exhibits a Kerr nonlinearity and possesses a transparency window out to $\lambda = 6$ μm. The microresonators were fabricated using diamond-point turning techniques to diameters between 330 μm and 1 mm, and then hand-polished to a finesse $\sim 50,000$. Light from a conventional telecommunications C-band laser coupled into the microresonators using a tapered fibre. When the pump light was resonant in the microresonator, spectrally pure sidebands could be seen, as shown in Fig. 1(a). Self-heterodyne measurements of the sidebands reveal them to be of a similar linewidth to the pump, indicating that the coherence of pump is preserved (Fig. 1(b)). We do not observe parasitic nonlinear processes, such as stimulated Raman scattering. We attribute this to the narrow Raman gain bandwith of crystalline magnesium fluoride. By tuning the pump wavelength by a multiple of the free spectral range of the microresonator, the wavelength of the generated parametric sidebands could also be tuned. The resulting phase-matching curve for five different microresonators is shown in Fig.1(c). We observe that, as the diameter of the microresonator is reduced, the zero-dispersion wavelength ($\beta_2 = 0$) is shifted out to longer wavelengths, shown in Fig 2(a). We verify, using finite-element simulations in Comsol Multiphysics, that this is due to contributions from geometric dispersion. The shift in zero-dispersion wavelength leads to increasingly large wavelength shifts for the parametric sidebands. Between the three largest microresonators characterised, we directly observe sideband generation out to 2.6 μm, with a corresponding short sideband at 1.1 μm, using a single C-band light source. Intermediate wavelengths can be generated in a quasi-continuous manner. The observation of longer wavelength sidebands is only limited by our experimental setup. In the smallest resonators, we further observe signatures of sidebands existing out to 3.8 μm. In addition to the quasi-continuous tunability described above, we also demonstrate regions of completely continuous tunability, accessed by fine-tuning the wavelength of the pump. As the pump is tuned into resonance, the increase in intracavity power is accompanied by an increase in resonator temperature, which red-shifts the central position of the resonance via a thermo-optic effect. Experimentally, we observe that as the pump is scanned, the sidebands follow. In Fig.2(b) and a tuning range of 10 GHz is observed, which corresponds to thousands of cold cavity linewidths.

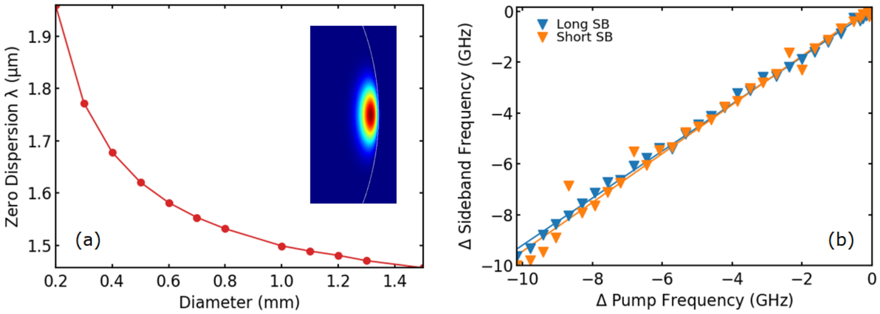

Figure 2. (a) Zero-dispersion wavelength for the fundamental mode, calculated using Comsol Multiphysics. Inset shows the mode distribution for the fundamental mode. (b) Change in sideband frequency as the pump frequency is finely tuned.

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