A chip-based micro-cavity optical parametric oscillator (μOPO)

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Abstract:
We report a micro-scale optical parametric oscillator (μOPO). Oscillations are observed at record low threshold values (170 micro-Watts) with highly ideal (97%) signal-to-idler photon emission. High conversion efficiencies (36%) are achieved.

OCIS codes: (190.4410) Parametric processes, (190.4970) Parametric oscillators and amplifiers, (230.5750) Resonators

Here we show how by controlling the cavity geometry of ultra-high-Q toroid microcavities[1], a transition from stimulated Raman to parametric oscillation regime is achieved. In order for parametric oscillations to efficiently occur, both energy and momentum must be conserved in this process[2,3]. In whispering-gallery-type resonators, such as micro-toroids, momentum is intrinsically conserved when signal and idler angular mode numbers are symmetrically located with respect to the pump mode (i.e. $l_{i,s} = l_p \pm N$). Energy conservation, on the other hand, is not expected to be satisfied a priori, since the resonant frequencies are discrete and, in general, irregularly spaced. As a result, the parametric gain is a function of the frequency detuning $\Delta\omega = 2\omega_P - \omega_I - \omega_S$, which effectively gives the degree to which the interaction violates strict energy conservation. Figure 1 shows the regime of detuning and cavity loading (K) in which parametric oscillation has a lower threshold than the competing Raman process. Threshold values are color coded as indicated.

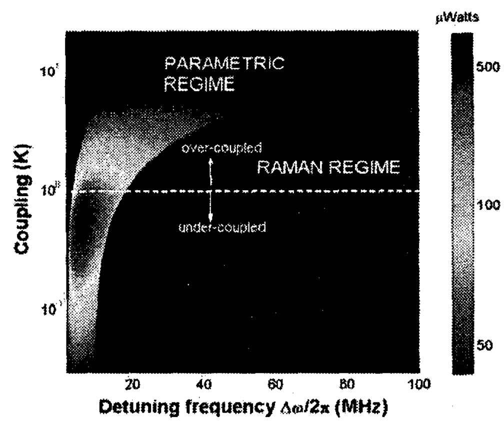

Fig. 1. Raman and Parametric oscillation in a micro-cavity with D=50 micron, d=4 micron and $Q_0=10^8$. The vertical axis denotes coupling strength K of the waveguide-resonator system. The dark blue region denotes areas where Raman oscillation occurs. The color-coded region corresponds to the parametric oscillation regime (where the parametric threshold is indicated by color in micro-Watts).

In order to achieve parametric oscillation, the detuning frequency must fall within the parametric gain bandwidth. A reduction of the toroidal cross-sectional area will produce a two-fold benefit in this respect. First, it increases the parametric gain bandwidth through its dependence on the effective parametric nonlinearity [2], while second, it reduces Δω. The latter occurs because of increased modal overlap with the surrounding dielectric medium (air) and hence flattening of the modal dispersion. Thus, the desired transition can be induced with toroidal geometries of high principal-to-minor toroid diameter (high aspect ratio D/d, where the principal diameter, D, denotes the outer cavity diameter and the minor diameter, d, refers to the smaller, toroid cross-sectional diameter).
We have experimentally verified this theoretical prediction, by fabricating micro-toroids having different aspect ratios. Coupling is achieved using tapered optical fibers[4]. For micro-toroids having an aspect ratio (D/d) in excess

of ca. 15 a transition (and a subsequent quenching of Raman[5,6]) to parametric oscillation was observed. Figure 2 shows a parametric oscillation emission spectra for a micro-toroid with d=3.9 micron, D=67 micron and Q_0=0.5×108. The parametric interaction in the micro-cavity causes emission of co-propagating signal and idler modes that are coupled into the forward direction of the tapered fiber. The generated signal and idler modes had identical oscillation threshold, within the experimental resolution set primarily by taper coupling variations (ca.±5%). Figure 3 shows the dependence of parametric threshold on waveguide-resonator coupling. The coupling is varied by adjusting the air-gap between a tapered fiber waveguide and the micro-toroid. The solid curve in the figure is based on a model.

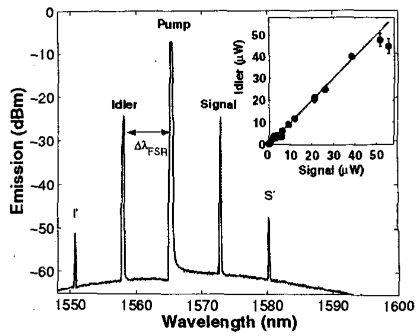

Fig. 2. Parametric-oscillation spectrum measured for a 67-micron–diameter toroidal micro-cavity. The pump is located at 1565 nm and power levels are far above threshold. The signal and idler are modes are spaced by twice the free spectral range (2×7.6 nm). For higher pump powers deviation is observed due to appearance of secondary oscillation peaks (I',S') (compare main figure). Inset: Measured Idler power plotted versus Signal power. The signal-to-idler power ratio is 0.97±0.03.

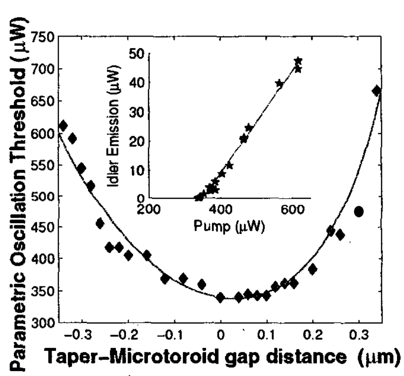

Fig. 3. The coupling-gap-dependence of the parametric threshold with respect to the critical coupling point (zero on the x-axis) measured using a 67-micron-diameter toroid micro-cavity. The minimum threshold occurs with the tapered optical fiber 0.04 micron under-coupled (with finite transmission of ca. 4%). The solid line is a theoretical fit. Inset: Idler emission versus pump power. The differential conversion efficiency from pump-to-idler was ~17% (and correspondingly 34% for pump to signal and idler).

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