Tunable lasers by optical parametric oscillation in photonic-crystal resonators

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Abstract: We demonstrate laser-wavelength access by design of optical parametric oscillation in photonic crystal resonators. Our experiments and theoretical modeling elucidate coupled bi-directional oscillation that we can jointly optimize for wavelength tuning and efficiency. OCIS codes: (140.3948) Microcavity devices; (190.4380) Nonlinear optics, four-wave mixing

Chip-scale optical parametric oscillation (OPO) enables the generation of arbitrary wavelengths from a single pump wavelength. Group-velocity-dispersion (GVD) engineering of integrated Kerr optical resonators enables phase-matching for triply resonant fields at pump, signal, and idler wavelengths for highly efficient degenerate four-wave-mixing based OPO [1]. The addition of a photonic crystal to the resonator (PhCR) by way of an edgeless modulation of the resonator inner wall opens a bandgap (BG), generating a blue- and red-shifted mode separated in frequency by BG (Fig. 1a) [2]. This allows for fine-tuning of a single resonator mode in the dispersion landscape, providing highly tunable phase matching. Importantly, by pumping the red-shifted PhCR mode in otherwise normal GVD resonators, the pump becomes effectively anomalous, enabling phase matching for OPO (Fig. 1a). Therefore, phase matching OPO by design is possible in PhCR by tuning the BG.

Experimentally, we increase the PhCR modulation amplitude (APhC) to control the magnitude of BG (Fig. 1a), providing access to arbitrary signal and idler wavelengths via OPO. Fig. 1b shows three different BG settings with OPO spacing increasing by 1 free-spectral-range (FSR). We model BG = 11.50, 13.25 and 15.25 GHz in a critically coupled PhCR using the Lugiant-Lefever Equation (LLE) [3]. Operationally, reflected light at the chip-facets can interfere with forward and backward propagating fields in the PhCR and produce both forward (pump co-propagating) and backward (pump counter-propagating) OPO from the chip. We use a modified LLE to model bi-directional OPO and find that the amount of light in the forward and backward direction depends on the amount and phase of the reflected light, ϕ [4]. We consider the theoretically optimal conversion efficiency, η, (sum of optical power into signal an idler frequency compared to input pump power) for a BG of 10 linewidths with normal GVD. We find that with 4% pump reflection in critically coupled devices with ϕ = 0 at the pump frequency, η ≈ 5% into both the forward and backward directions (η ≈ 10% total). By going to an over coupled regime (κc = 3κc), the same device parameters result in higher η ≈ 12% into both forward and backward direction. Note that higher η comes at the cost of higher threshold power [1]. We consider intentionally recycling pump light back towards the resonator by an engineered on-chip reflector. We find that reflecting 90% of the pump light at a reflector after the PhCR where ϕ = 0 at the pump

Fig. 1: (a) PhCR schematic and scanning electron microscope image of PhCR with APhC which opens a BG, effecting the integrated dispersion, D_int, as shown in the bottom left. The red-shifted BG mode enables phase matching for OPO in otherwise normal GVD resonators as shown by the blue-dashed line. (b) Ordinary LLE simulations of OPO in a fixed geometry PhCR with varied BG, which tunes the OPO output. (c) Schematic of a PhCR with an integrated pump wavelength reflector to recycle pump power into the PhCR with designable phase, ϕ. Simulated comb power traces in the forward and backward direction in a modified LLE with a 90% pump reflector in the over coupled regime.
frequency, $\eta \approx 24\%$ conversion efficiency is possible in both the forward and backward direction in the over-coupled regime (total $\eta \approx 48\%$) (Fig. 1c).

We have tested several PhCR devices with and without reflectors to explore $\eta$ into both forward and backward directions. Fig. 2a shows the transmitted light as a function of laser detuning at three measured BG = 9.49, 11.14, 12.51 GHz (APhC = 79, 96 and 110 nm) in over coupled PhCRs without a pump reflector. An etalon fringe is clearly visible in the transmitted signals due to reflections at the chip-facets. We pump these three PhCRs to $\approx 1.3$ times the measured OPO threshold power and monitor the forward and backward comb power, which are the pump-filtered optical signals measured on a photodiode. Experimentally, we measure $\eta \approx 5, 6, 5\%$ in the forward direction and $\eta \approx 10, 3, 5\%$ in the backward direction for BG = 9.49, 11.14, 12.51 GHz (total $\eta \approx 15, 9, 10\%$). The bi-directional LLE model predicts that $\phi$ controls the relative $\eta$ into the forward and backward direction, which we find experimentally in Fig. 2b and the corresponding optical spectra in Fig. 2c. We find these three BG tune the OPO spacing in 1-FSR steps as shown in Fig. 2c where the vertical dashed lines denote frequency spacing of 1-FSR (955 GHz). Finally, we have also tested PhCRs with pump wavelength reflectors in critically coupled devices. Fig. 2d shows the forward and backward OPO optical spectra scaled to on-chip pump powers in a device with APhC = 12 nm and target pump reflection of 90%. We measure $\eta \approx 13, 3\%$ in the forward, backward direction (total $\eta \approx 16\%$).

In conclusion, we have demonstrated tunable laser wavelength by design using PhCR based OPO. The OPO spacing depends sensitively on APhC which controls the PhCR BG. For finer than FSR laser wavelength tuning, thermal tuning can be employed to shift the resonator modes by several nanometers. We show that bi-directional PhCR OPO operates with high $\eta$ (experimental total $\eta \approx 15\%$) and that by engineering a pump recycling reflector, total $\eta$ approaching 50% is theoretically possible for over coupled PhCRs.

References
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