Cavity Length Resonances in a Singly Resonant Optical Parametric Oscillator with a Volume Bragg Grating

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Abstract: Resonant output energy enhancement in a singly resonant nondegenerate type-I optical parametric oscillator with a volume Bragg grating output coupler is demonstrated when there is a low fraction cavity length ratio between laser and OPO.

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The output energy from a pulsed optical parametric oscillator (OPO) will in general decrease as the cavity length is increased. The causes for this are increased diffraction losses in the longer cavity, especially if plane mirrors are used, and longer build-up time because of the increased roundtrip time. It has been shown that under certain conditions peaks in conversion efficiency appear when the relation between the optical path lengths of the pump source and OPO cavities form a low fraction in a doubly resonant OPO pumped by a multi-longitudinal mode laser [1]. The suggested explanation was that when the roundtrip times of the pump laser matches that of the OPO the signal and idler will experience the same pump phase at each roundtrip so that the phases can adapt optimally in order to maximize the parametric gain and the efficiency comes close to the single-mode pump case. From this explanation no resonances are expected in a singly resonant OPO (SRO) configuration as the idler is not constrained by the cavity boundary conditions and thus can acquire any phase to compensate for partially random phase modulation of the pump. Weak effects attributed to amplitude modulations in the pump were found in simulations of a broadband SRO [2].

Volume Bragg gratings (VBG) have been shown to be an efficient way of reducing the spectral width of OPOs with broad gain bandwidth [3-6]. This is especially interesting in near degenerate quasi phase-matched OPOs that have an important application in generating narrow bandwidth radiation at wavelengths longer than 2 μm for pumping of ZGP OPOs [4,5]. A cavity using a VBG resonant off degeneracy also ensures a singly-resonant and spectrally narrow operation. We show that there exist strong cavity length resonances in a SRO with a VBG output coupler and suggest an explanation.

The pump laser in our experiment was a diode-pumped multi-longitudinal mode Nd:YVO_4-laser running at 100 Hz pulse repetition frequency. The pump pulse energy was kept constant at 1.8 mJ in 9 ns long pulses during these experiments. With the help of a Michelson interferometer the pump laser spectrum was characterized to have 28 GHz FWHM bandwidth and 1.2 GHz mode separation.

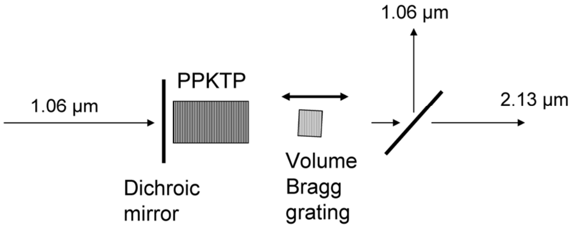

Fig. 1. Schematic of the OPO setup.

The OPO used a 20 mm long PPKTP crystal with a 38.85 μm domain grating over 16 mm of the length. The crystal was surrounded by a cavity consisting of a flat dichroic incoupling mirror and a VBG. The OPO setup is illustrated in Fig. 1. The VBG had nominally 50% peak reflectivity with 0.5 nm FWHM spectral width at 2122 nm. All surfaces of the PPKTP crystal and the VBG were AR-coated and tilted with respect to the beam direction to avoid broadband feedback. As only the incoupling mirror is aligned perpendicular to the pump direction the cavity is perfectly singly resonant and there is no pump feedback in the cavity. Fabry-Perot measurements of the OPO signal and idler spectra, shown in Fig. 2, which revealed a clear longitudinal mode structure in the signal and an unstructured idler verifies this [6]. As a reference measurement using a DRO, the VBG was exchanged for a flat broadband 50% reflecting mirror covering the signal and idler bands. The output spectrum of this OPO was approximately 200 nm wide. The positions of the incoupling mirror and PPKTP crystal were fixed while the output coupler (VBG or dielectric mirror) was translated and the OPO output energy was recorded.

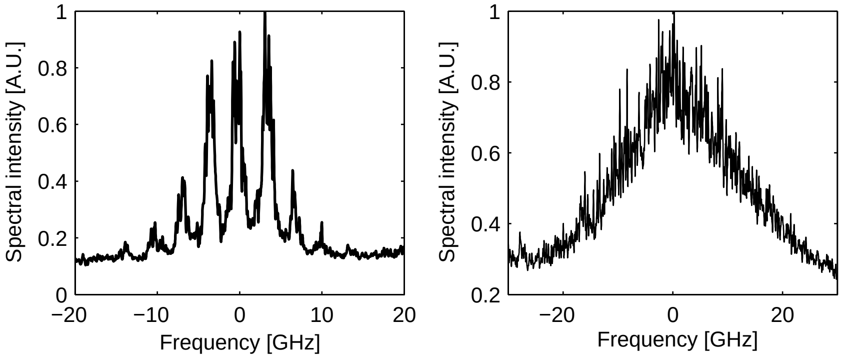

Fig. 2. Spectra of signal (left) and idler (right) of the OPO with VBG output coupler measured for the shortest possible cavity length. Signal and idler are separated by 13 nm (860 GHz).

The OPO average output energies for the two different output couplers and varying cavity optical path lengths are shown in Fig. 3. For each position the energy of 1000 pulses was averaged. The general trend for both cases is as expected that the output energy is reduced as the cavity length increases. Both OPO:s show a clear increase in output energy when the OPO cavity is half the length of the laser cavity. Another resonance clearly visible in DRO is at the cavity length of one-third of the laser cavity. Due to the finite beam penetration depth in the VBG it was impossible to scan entirely through this resonance for the SRO, but one flank of the peak can still be obesrved. Weaker peaks are also found when the relations between the cavity lengths are two and three fifths. By subtracting the linear slope from the data points around the peak at half the laser cavity path length the OPO energy enhancement can be estimated, as shown in Fig. 3. The peak amplitudes are 72 μJ and 40 μJ for the VBG SRO and the mirror DRO, corresponding to an output energy enhancement of 36% and 16%, respectively. The FWHM peak widths are estimated to 3.0 mm and 1.3 mm for the SRO and the DRO, respectively. At one third of the laser cavity path length we find a peak width of 0.8 mm and a peak amplitude of 29 μJ for the mirror cavity DRO. For the VBG SRO a peak amplitude of approximately 40 μJ can be estimated, although only half of the peak was available due to the finite scan range, as described above. These peak amplitudes correspond to the OPO energy enhancements of about 14% and 10% for the SRO and DRO case, respectively. The weak peaks at two and three fifths are clearly narrower than the 1/2 peaks.

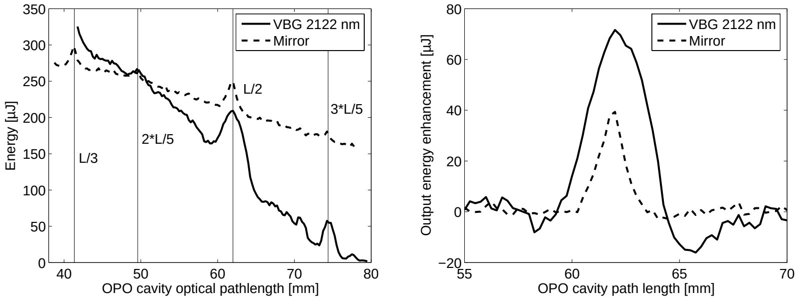

Fig. 3. Left: Average OPO pulse energy as a function of cavity length, with VBG (solid line) and mirror (dashed line) output couplers. The vertical lines signify low fractions between the OPO and laser cavity optical path lengths. Right: Energy enhancement due to resonance when the OPO cavity path length is half of the laser cavity path length.

The resonant enhancement effect in a DRO has been observed and described in [1], where it was also stipulated that the effect exists under conditions when the pump coherence time is longer than group-velocity walk-off between pump and signal and between signal and idler, i.e. when the pump and the DRO cavity resonance matching is maintained. In the case of the SRO this triple-wave mode matching does not exist, so in order to explain the resonant SRO output enhancement effect one needs to consider longitudinal mode locking between two or more pairs of pump and signal modes with the nonresonant idler performing a role of cross seeding. This mechanism provides both the additional constraints which will manifest in a necessary matching of the laser and SRO lengths as well as a mechanism for coherent cross-amplification of different longitudinal signal modes. The sketch of this mechanism for the case of L/3 resonance is shown in Fig. 4. Here the longitudinal modes for the pump and signal are shown with the first mode frequency set to zero, i.e. after subtracting the carrier frequencies. Moreover the cavity modes are shown equidistant, which is a good approximation considering the relatively narrow bandwidths of the pump and the SRO signal, 30 GHz and 10 GHz, respectively. In the L/3 resonance case, every third of the pump longitudinal mode will coincide with the signal mode. Moreover, every such coinciding pair will produce the idler wave at an identical frequency ω_i. For instance, consider that one of the SRO modes has initially the largest gain and starts oscillating first, generating idler ω_i with the phase adjusted for maximum efficiency, $\varphi_{p,n} - \varphi_{s,m} - \varphi_i = \pi/2$. This occurs automatically in a SRO because the idler phase is not constrained by the cavity boundary conditions. The generated idler will act as a seed for the other signal modes in coincident signal-pump modes. However, in this case the newly generated signal phase will be constrained by the seeding idler and the pump mode: $\varphi_{s,m+1} = \varphi_{p,n+1} - \varphi_i - \pi/2$. The phase constrain produced by this cascade should result in a resonant enhancement of the SRO output as long as the phase of the pump modes are to some degree correlated. The universal idler seed ensures that the phase correlations of the pump modes will be directly imprinted on the phase correlations of the SRO signal. The amount of the resonant enhancement in the SRO output obviously depends on the spectral bandwidth of the SRO due to the variation of the mode separation, owing to the group delay dispersion. This explains why the enhancement is larger and the resonance peak is broader in the OPO with the VBG output coupler as compared to the OPO containing the broadband mirror output coupler. This enhancement mechanism also depends on the mutual coherence of the longitudinal modes of the pump. In the case of total coherence, as in mode-locked lasers, the SRO output enhancement mechanism is analogous to synchronous pumping. In the case of total incoherence of the pump, the enhancement mechanism should be inefficient as the generated signal phase determined by the idler seed and the pump may not correspond to the phase required by the boundary conditions of the SRO cavity. The amplitude at the particular n/m fraction of the pump laser cavity length essentially depends on how many coincident signal-pump mode pairs are available within the signal bandwidth, i.e. the resonance amplitude will be inversely proportional to the denominator m. This is in good agreement with our experimental results.

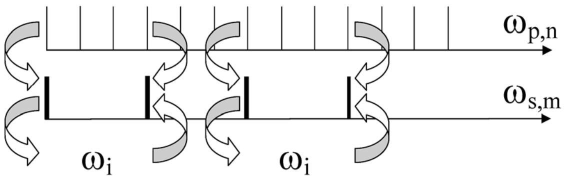

Fig. 4. Sketch illustrating mechanism of resonant enhancement of the SRO output by cross seeding of the longitudinal signal modes by the idler wave generated by coincident pump-signal mode pairs.

In conclusion we have shown that the phenomenon of enhanced OPO efficiency for a fractional relation between the OPO and the pump laser cavity optical path lengths is present for both singly and doubly resonant cavities. In the SRO the resonance enhancement of the OPO output becomes possible when the idler wave generated by a single pair of pump and signal longitudinal modes can coherently seed a family of equidistant signal longitudinal modes. This mechanism adds an additional phase constraint to the SRO, and is a requirement for resonant OPO output enhancement when pump and parametric cavity length ratio is an integer number or a fraction of integers. Important requirements for realizing this effect is spectral narrowing of the SRO output, e.g. by a VBG output coupler, and at least partial coherence of the laser longitudinal modes.

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