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Spectral Properties of Optical Parametric Oscillators

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Abstract

Optical parametric oscillators (OPOs) are useful devices to generate tunable radiation. The tuning characteristics of OPOs can lead to their utility in remote sensing applications. We have investigated injection-seeded OPOs to generate narrow-band Mid-IR radiation for this purpose. OPOs exhibit a resonance structure similar to that of a laser’s cavity limiting the frequency choices available. Also, the coupling of the electric fields of the three interacting waves can generate cavity resonances for OPOs which have no cold cavity resonances (i.e. non-resonant OPOs). The potential for generating multiple frequencies simultaneously from a single OPO is discussed. The generation of multiple output frequencies is accomplished by injecting either multiple signal or multiple pump frequencies to the OPO. A seeded SRO is found to be well-suited to generating spectrally pure and stable multi-line output when the input pump field is multiple frequency. The generation of sideband frequencies during multiple seeding is also observed experimentally and addressed theoretically. The spectral purity of the OPO output is related to the frequency separation of the multi-line input as compared to the OPO cavity resonance structure.

Introduction

The generation of optical pulses with tailored spectral properties may be required for accurate background subtraction in DIAL measurements. Injection-seeded optical parametric oscillators (OPOs) are a potential source for high power, spectrally formatted pulses over a wide range of wavelengths. In order to assess the applicability and performance of various OPO architectures in generating specific spectral formats, the OPOs were modeled both analytically and numerically. The analytic treatment enables investigation of cavity resonance behavior. The numerical model developed enables tracking the evolution of pump, signal, and idler fields in a general OPO architecture where each of the widely spaced interacting fields can contain multiple frequency components.

In particular, we have investigated the simultaneous generation of multiple frequency output idler pulses in both singly resonant (SRO) and “non-resonant” (NRO) parametric oscillator devices. Three-wave mixing between the matrix of desired pump, signal, and idler frequencies can also lead to the generation of unwanted frequency side bands. The generation or suppression of these undesirable frequencies is dependent on numerous aspects of the OPO including which fields are injected into the OPO, the OPO architecture, frequency separation between the injected fields, and crystal alignment. The predicted behavior of the OPOs is compared with experimental observations.

Numerical Model Description

The geometry modeled is a linear two mirror OPO. An SRO consists of highly transmissive optics at the pump and idler wavelengths and reflective optics at the signal (resonant) wavelength. Maximum cavity enhancement occurs when the cavity round trip length is an integer multiple of the signal wavelength. An NRO has one mirror which is reflective at the pump and signal wavelengths but transmissive at the idler wavelength (output coupler), while the other mirror is transmissive at the pump and signal wavelengths and reflective at the idler wavelength (input coupler). Since there is only one reflective mirror for each wavelength there are no cold cavity resonances in an ideal NRO.

The standard three-wave mixing equations are solved in the nonlinear crystal in the plane-wave approximation. The model is time dependent and includes finite phase mismatch ($\Delta k \neq 0$). For a single set of pump, signal, and idler waves this yields three equations, each with a single 3-wave interaction term. In order to treat multiple frequency components, fields are defined at three central frequencies as $p_0$ at $\omega_p$, $s_0$ at $\omega_s$, and $i_0$ at $\omega_i$, for the pump, signal, and idler, respectively, and at side band frequencies of $\omega_p+i\Delta \omega$, $\omega_s+i\Delta \omega$, and $\omega_i+i\Delta \omega$ as $p_{ij}$, $s_m$, and $i_{im}$, respectively. Energy conservation only permits interaction of the pump, signal, and idler components such that $j = m + n$. For $n_{max} = n_{max} = n_{max}$ the possible interactions lead to $8m_{max}+3$ coupled equations. Each of these equations now can have multiple three-wave interaction terms provided $j = m + n$ is satisfied. Because of dispersion in the crystal, each interaction term will have different phase mismatch. The crystal dispersion will also result in a
different phase lag for each frequency when propagating through the cavity. These cavity length phase factors, \( \exp(i k L_{\text{cav}}) \), are applied to the fields at the cavity mirrors as part of the boundary conditions for the OPO.

Several algorithms for following the temporal evolution of the fields in the OPO are utilized depending on the problem requirements. One approach divides the temporal pulse into increments of the cavity round trip transit time. For each time slice the appropriate boundary conditions are applied at the mirrors and the interacting fields are stepped through the cavity, solving the interaction equations in the crystal. This approach requires choosing a common phase velocity for the interacting fields and has a fixed temporal resolution. A direct finite difference algorithm is also used which discretizes the OPO propagation direction and time on a \((z,t)\) grid. This scheme, which uses a Wendroff central difference operator to solve the first order hyperbolic equations, can use arbitrarily small time steps to investigate temporal features not adequately resolved by the round trip differencing algorithm. The finite difference algorithm has the disadvantage of being much more memory and CPU intensive than the round trip algorithm.

**Results**

All cases presented consider a 30 mm LiNbO₃ crystal cut at \(-47^\circ\) to the optic axis and type I phase matching. The OPO cavities are nominally 85 to 100 mm between mirrors and absorption and transmission losses are neglected for these qualitative studies. The input pump and signal wavelengths are 1.064 and 1.51 \( \mu \text{m} \), respectively, resulting in an output idler wavelength of 3.60 \( \mu \text{m} \). The OPOs are typically pumped with an injection-seeded Nd:YAG laser with a nearly Gaussian temporal pulse shape of 15-20 ns duration and input energies ranging to \(-200\) mJ. Beam diameters are assumed to be 6 mm.

**NRO cavity resonances**

As discussed in reference 1, the NRO does exhibit cavity resonance behavior even with perfect NRO mirrors, i.e. no pump or signal reflectivity at the input coupler and no idler reflectivity at the output coupler. The existence of cavity resonances can be shown analytically from the steady-state three-wave mixing equations assuming the undepleted pump approximation. The idler field incident on the input coupler after propagating through the NRO cavity, \( E_{i,circ} \), is related to the input signal field, \( E_{s,0} \), by

\[
E_{i,circ} = \frac{E_{s,0}}{1 - |g|^2 \exp(i\delta)r_p r_s r_i}
\]

where \( g \) is the single pass gain, \( r_p, r_s, \) and \( r_i \) are the mirror reflectivities at the reflecting optic for the pump, signal, and idler frequencies, respectively. The phase factor \( \delta \) is given by

\[
\delta = \Delta k L_{\text{crs}} + \frac{4\pi}{\lambda_i} \left( L_{\text{cav}} + [\eta_i - 1] L_{\text{crs}} \right)
\]

where \( \Delta k \) is the phase mismatch in the non-linear crystal, \( \eta_i \) is the refractive index at the idler wavelength, \( \lambda_i \) and \( L_{\text{crs}} \) and \( L_{\text{cav}} \) are the lengths of the crystal and cavity, respectively. Equations 1 and 2 describe a resonance structure which is similar to that of an SRO cavity. However, the resonance results from the coupling of the phases of the fields by three-wave mixing rather than from feedback of a single frequency between two mirrors. This resonance behavior is also seen with the time-dependent numerical calculation and experimentally. Figure 1 presents the numerically predicted conversion efficiency as the injected signal frequency is varied. The regular 1.2 GHz spacing of the longitudinal modes is also observed experimentally as shown in Figure 2. Figure 2 presents the free running spectrum observed for a NRO and the relative locations in frequency space which could be seeded (seed laser frequency must match an NRO resonance). The NRO in Figure 2 was pumped at approximately 1.5 times the threshold energy.

**Multi-line output with an NRO**

We investigate the simultaneous generation of two closely spaced frequencies for use as the on and off resonance beams for two color DIAL. The generation of two output idlers is facilitated by seeding the NRO with two commercial tunable diode lasers with output powers \(-1\) mW. Typical frequency separation of the injected signals is 30 GHz.

Because of the existence of resonances in the cavity, the frequency of both injected signals must be mode matched to the NRO resonances. Given this constraint, the sensitivity of the output to the variation of the propagation angle relative to the crystal optical axis is investigated. The calculated results for an ideal NRO pumped with a 70 mJ, 15 ns FWHM pump are shown in Figure 3. The input signal seed powers are 500 \( \mu \text{W} \). The relative output on the two lines of interest is found to be a sensitive function of crystal angle. This results in significant fluctuations in the relative energies in the two lines on a pulse-to-pulse basis given the typical pointing stability of the pump laser of up to 35 \( \mu \text{rad} \). This angle sensitivity is evident in the experimentally observed anticorrelation between the energy fluctuations of the two output lines as shown in Figure 4. Note that the total output energy is relatively constant while the energy partitioning varies significantly in Figure 3. This is also observed experimentally.
and can be seen from the normalized deviation plots presented in Figure 5. The observed deviations for the individual lines are significantly broader than the deviation of the sum of the two lines.

Figure 1. Time-dependent Numerical calculations predict a longitudinal mode structure for an ideal NRO.

Figure 2. Experimentally observed discrete longitudinal mode structure of an NRO: left) free-running spectrum; right) seeding observed only at wavelengths corresponding to longitudinal modes.
Figure 3. Energy balance between the desired output frequencies as a function of the crystal angle in a dual-seeded NRO. The frequency separation between the lines is 30 GHz.

Figure 4. Experimentally observed anticorrelation between pulse to pulse energy fluctuations for a dual-seeded NRO.
Figure 5. Statistical distribution of pulse to pulse energy fluctuations observed experimentally for a dual-seeded NRO. The distributions presented on the left panel are the fluctuations for each line individually and the right panel is the fluctuation of the sum of the two lines. Also note more than 10% of the total converted energy resides in side band frequencies not of interest for a DIAL measurement. These sidebands are pumped as a result of the mixing of the multiple input signal and output idler frequencies present in the cavity and have been observed experimentally.

The relative output energy between the two desired lines for the NRO is predicted to be a sensitive function of the seed laser input power ratio. Figure 6 presents the relative output on the principal idler lines as the seed power is varied, keeping the total input seed power at 1 mW. Experimentally the input seed powers are very stable. Therefore this effect would have less impact on a DIAL experiment than the angle sensitivity.

Figure 6. Energy balance between the desired output frequencies as the input power is varied between the input seeds in a dual-seeded NRO. The total input seed power is 1 mW and the frequency separation between the lines is 30 GHz.
Multi-line output with an SRO

An alternative approach to generating multiple simultaneous frequencies is to utilize an SRO. If the same single-pump, dual-signal input scheme is used a number of the NRO characteristics will still be present. These include requiring both seeds to be matched to the OPO cavity, limiting the flexibility in frequency separation. Having both seeds separated by a multiple of the cavity spacing also ensures the sideband frequencies will also be cavity modes of the SRO, leading to the generation of unwanted frequencies as in the NRO cavity. The output energy partitioning is still a function of the propagation angle, as shown in Figure 7, but it is a much smoother function than in the NRO. The pump used in Figure 7 was a 140 mJ, 15 ns FWHM Gaussian pulse and the frequency separation of the signals was 30.5 GHz. The SRO output coupler has 50% reflectivity at the signal wavelength which yields an OPO output coupling similar to the NRO.

Changing the OPO pumping configuration to one low-power signal frequency and a two-frequency pump field results in much better output spectral purity and significantly reduced angular sensitivity. An example of a two-frequency injection-seeded Nd:YAG laser has recently been demonstrated (see reference 3). In this configuration the SRO cavity is locked to a single frequency and the frequency separation is chosen by the input pump frequency spacing. The multiple pump frequency SRO is found to generate exceptionally clean frequency output at the desired lines and is much less sensitive to laser pointing angle variations, as seen in Figure 8. The input pump fields used for Figure 8 were 70 mJ, 15 ns FWHM Gaussian pulses separated in frequency by 30 GHz.

The injection of multiple pumps into an SRO can lead to degraded spectral purity if the frequency separation of the input fields is a multiple of the cavity resonance of the injected signal wave. In this arrangement, the additional signal frequencies which are generated from the matrix of three-wave interactions will also be resonant with the SRO cavity, leading to poor discrimination of the output fields. This is illustrated in Figure 9. The SRO output with matched resonance spacing has similar spectral impurities to those predicted for an unseeded SRO. Seeding the SRO enables the pump energy to be effectively channeled through the seeded cavity mode frequency to the desired output idlers only if the frequency separation of the input pump fields is not a multiple of the cavity mode spacing.

The generation of multiple frequencies by injecting multiple pumps and a single seed into a SRO has the additional property of accurately mapping the relative input energies of the pumps to the corresponding idler frequencies. This can be seen from Figure 10 where the input 200-ns pump pulse energy was fixed at 300 mJ but the distribution of that energy was varied between three input frequencies. The total conversion efficiency is nearly constant. The conversion efficiency and threshold behavior of the SRO are determined by the total input pump energy because of the single signal wave generation in the cavity. However, the idler energies are determined by the individual energy partitioning of the pump fields. This suggests the SRO frequency conversion will not add significantly to pulse-to-pulse energy fluctuation in a DIAL system.
Figure 8. Energy balance between the desired output frequencies as a function of the crystal angle in a multiple pump frequency SRO. The frequency separation between the lines is 30 GHz.

Figure 9. Output frequency content for an SRO pumped with two pump frequencies separated by a multiple of the cavity mode spacing.
Figure 10. Relative idler output energy as the ratio of the energy of the input pump fields is varied. The total input energy to the seeded SRO is fixed at 300 mJ and the input energy at $p_{-1}$ is fixed at 100 mJ.

Summary

A theoretical model capable of describing the operation of OPOs with frequency formatted pulses is presented. The time-dependent plane-wave model solves the three-wave interaction equations for a matrix of pump, signal, and idler fields in a general OPO cavity. The model has multiple algorithms for treating the temporal dependence of the pulses that afford flexibility in analyzing the temporal response of OPOs over a wide range of input characteristics.

The modeling of the NRO shows the existence of cavity resonances due to the coupling of the three interacting fields even under ideal conditions where there are no cold cavity resonances. The existence of these resonances can be shown analytically and has been observed experimentally. This resonance structure requires seeding of the NRO at discrete frequencies as is required in a SRO.

Simultaneous generation of multiple idler frequencies for DIAL has been investigated using both NROs and SROs. The dual-seeded NRO output is found to be very sensitive to pump pointing stability, consistent with experimental observations. An alternative approach to generating simultaneous idler outputs utilizes an SRO pumped by multiple pump fields and seeded with a single low power signal field. This arrangement is shown to generate spectrally purer output fields than the NRO and can accurately transfer the relative magnitude of the input pump field amplitudes to the idler output. This could be useful in generating amplitude and phase modulated outputs from the OPO to increase the alternatives for various DIAL detection and noise reduction scenarios.

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References