Effect of Cavity Design on Optical Parametric Oscillator Performance

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Effect of Cavity Design on Optical Parametric Oscillator Performance

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Abstract

The effect of resonator cavity design on parametric oscillator performance is investigated theoretically. Certain unstable resonators produce superior energy conversion and beam quality than traditional resonators.

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Summary

Optical parametric oscillators (OPOs) offer an efficient means of generating coherent, tunable radiation in frequency regimes not directly accessible with current laser technology. The utility of OPOs depends on their ability to efficiently convert the pump light into the longer wavelength signal and idler beams and the quality of the output beams produced. These characteristics are dependent both on the input pump laser and the resonator cavity design. Recent experimental results have indicated that unstable resonators have advantages over more traditional flat-flat or stable resonators in achieving high conversion efficiency with good output beam quality. In this paper we investigate the OPO performance theoretically as a function of the resonator cavity design. The reported experimental findings of references 1 and 2 are supported by our calculations.

The model developed is time-dependent and includes diffraction, three-wave mixing, crystal absorption, and variable reflectivities and curvatures of the mirrors. The model solves the coupled field equations for the three waves using a split-step operator approach in the crystal. The three-wave mixing and crystal absorption are treated with a second-order, predictor-corrector algorithm and the diffraction is treated using Fourier transform techniques. The propagation is limited to uniaxial crystals or biaxial crystal propagation in a principal crystal plane. The time dependency is treated by discretizing the pulse envelope in increments of the cavity round trip time. Each of these time slices is propagated through the cavity applying the appropriate boundary conditions at the mirrors. Fields can be injected (or extracted) at both mirrors to accommodate experimental conditions. Non-ideal input fields are treated by permitting Gaussian, super-Gaussian, and Hermite-Gaussian transverse beam shapes as well as phase aberrations described by Zemike polynomials. The input temporal pulse shape can be either Gaussian or super-Gaussian and can be specified individually for each input field.

The pump laser assumed for the study is a pulsed YAG laser at 1.064 μm with a 20 ns FWHM Gaussian temporal pulse profile. The parametric oscillator studied is singly-resonant and has a 30 mm LiNbO₃ crystal. The crystal is cut at the phase-matching angle for generation of 1.5 μm signal and 3.6 μm idler waves (~47° to the crystal z-axis). The signal wave is resonated in the cavity and the mirrors are assumed 100% transmissive for the pump and idler waves. The output coupler is assumed to reflect 60% at the signal wavelength and the only loss considered is a 10% transmission of the signal wave at the input coupler. A linear cavity geometry is assumed with a physical length of 125 mm.

Three cavity types are considered, a long-radius, hemispherical stable cavity, a flat-flat cavity, and a positive branch, confocal unstable cavity. The stable resonator supports a 10 m radius back mirror and a flat output coupler. Multiple unstable resonator magnifications are used ranging from M=1.02 to M=1.2. The unstable resonators use a uniform partially-transmitting curved output coupler in contrast to a spot mirror. This is considerably simpler experimentally and affords more uniform near-field output profiles of the resonated wave. The effective unstable resonator feedback is a combination of the beam expansion and the output coupler reflectivity. The reflectivity of the output coupler is varied to maintain approximately constant effective feedback between the different unstable resonator magnifications and the stable and flat-flat cavities.

The energy output generated with the different cavity types is shown in Figure 1 for an unaberrated, Gaussian spatial input pump profile with a waist of w₀=3 mm. The conversion efficiency is the poorest for the stable resonator, particularly at high input pump energies. The stable resonator mode for this cavity configuration is ~0.7 mm, which is significantly smaller than the pump size. This poor mode
matching results in reduced energy conversion. As the magnification of the unstable resonator increases, the output idler energy increases. The magnification cannot be continually increased, however, since the effective output coupling is dependent on both the magnification and output coupler transmission. At $M=1.2$ the beam expansion results in a signal intensity reduction of 31% on each round trip. For an effective output coupler reflectivity of 60% the transmission of the signal wave for this magnification is only 13.5% (effective reflectivity is $R_{eff}/M^2$). At this magnification the usable output signal energy has decreased significantly compared to the lower magnification cavities as seen in Figure 2 for a 100 mJ input pump. The flat-flat resonator is shown as $M=1$ and the stable resonator is included at $M=0.96$ for comparison.

![Figure 1. Comparison of the energy conversion for unstable, flat-flat, and stable OPO resonator cavities.](image)

![Figure 2. Comparison of the OPO output energy as a function of unstable resonator magnification for a 100 mJ input pump pulse. The flat-flat cavity result is plotted at $M=1.0$ and the stable cavity is plotted at $M=0.96$ for comparison.](image)

Similar trends in the output energy conversion are seen for pump beams with super-Gaussian spatial profiles. For a super-Gaussian beam with a radius of 3 mm the output energy is ∼20% lower for the flat-flat and unstable cavities at 100 mJ input pump energy. The peak intensity of the Gaussian beam is higher than that of the super-Gaussian beam for equivalent radii and energy (∼60% higher). This larger peak intensity enables the Gaussian pump to reach threshold earlier in the pulse than the pump with the super-Gaussian spatial profile, resulting in increased energy conversion. The stable cavity again converts the least amount of energy and the conversion is significantly lower than with the Gaussian input pump (2 verses 6 mJ for the Gaussian and Super-Gaussian pumps, respectively). The transverse beam shape effect is more pronounced with the stable resonator because of the poor mode matching with the pump beam size. Since the stable cavity mode is smaller than the pump beam only the central portion of the pump beam is efficiently converted and in this region the super-Gaussian intensity is significantly lower than with the Gaussian profile.

The output beam divergence is also a function of the cavity type as seen in Figure 3 for a 100 mJ Gaussian input pump pulse. Multiplication of the beam divergence by the wavelength yields the half angle which contains ∼82% of the beam energy. The unstable resonator produces the output with the minimum divergence. At $M=1.2$ the output beams are approximately 1.2 times diffraction limited based on the divergence of a Gaussian beam with $w_0=3$ mm. Note the beam quality is very good for magnifications as small as $M=1.1$. This is potentially useful for OPOs operated at lower energies where increased feedback is required for efficient energy conversion.
The unstable resonator also performs better than the more traditional resonators when pumped by aberrated input beams. The energy conversion for an astigmatic input pump beam is shown in Figure 4. The input pump has 1 λ of astigmatism across the 3 mm radius and has a super-Gaussian transverse intensity profile. The 1 λ of astigmatism results in an input beam quality of ~3 TDL as compared to a 3 mm radius flat-phase, flat-top beam. The conversion efficiency is highest for the unstable resonator and lowest for the stable cavity. The output beam divergence also was best for the unstable resonator which produced an output beam quality approximately the same as the input pump beam over the range of input energies investigated. The output beam quality from the flat-flat and stable cavities degraded monotonically as the input pump energy increased, the flat-flat cavity producing the lower output divergence. Although the flat-flat cavity performed better at the 1 λ aberration level the stable cavity was found to perform comparably or better than the flat-flat cavity with larger (2-3 λ) astigmatic aberrations, particularly at higher input pump energies. With these higher aberrated conditions the unstable resonator still performed better than the other resonator types.

In summary, the effect of resonator cavity type on OPO performance has been investigated theoretically with a time-dependent model including diffraction, three-wave mixing, and pump beam aberration effects. Under the conditions analyzed, an unstable resonator is found to out perform flat-flat and stable resonators in both energy conversion and output beam divergence. This result is found with unaberrated and astigmatically aberrated input pump beams.

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