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# Nanosecond optical parametric oscillators produce phase modulated light

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## Abstract

We have found that nanosecond optical parametric oscillators pumped well above threshold by single longitudinal mode pulses produce signal and idler light that is nearly purely phase modulated, even for unseeded operation.

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# Nanosecond optical parametric oscillators produce phase modulated light

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## Introduction

Nanosecond optical parametric oscillators (OPO's) oscillate on multiple longitudinal modes unless frequency narrowed using intracavity elements or injection-seeding. Unseeded oscillation builds from quantum fluctuations in the signal and idler fields, so the energy distribution among modes fluctuates from pulse to pulse reflecting the random nature of the start-up noise. In multimode lasers, the random phases and amplitudes of the modes result in strong amplitude modulation (AM). In contrast, we show that modes of an OPO pumped by temporally smooth pulses from a single-longitudinal-mode laser have phase relationships that minimize AM, resulting in almost purely phase modulated (PM) signal and idler light. This difference between lasers and OPO's is due to the strong coupling among the OPO modes via back conversion of the signal and idler into pump light.

Direct demonstration of AM suppression requires detection bandwidths beyond those available, so we report several less direct measurements capable of detecting AM.

The experimental apparatus is shown in Fig. 1. The OPO is pumped by temporally smooth 7 ns duration (FWHM) 532 nm pulses with 0.6 mm diameter (FWHM) Gaussian spatial profiles. A Ti:Sapphire laser seeds the OPO at the 800 nm signal wavelength, and a phase modulator can impose a PM spectrum on the seed at the 3.66 GHz OPO mode spacing. The singly-resonant KTP ring oscillator has an $R = 0.84$ output coupler and is locked to the signal wave. The unseeded OPO bandwidth is $\sim 2\ \mathrm{cm}^{-1}$.

## AM seeding

When seeded with AM light, the OPO tends to produce pure PM light. AM seed light is generated by reflecting PM light off a Fabry-Perot étalon. The seed wavelength is tuned so the étalon transmits one PM sideband, and reflects a combined AM-PM spectrum with unequal sidebands. When pumped well above threshold, the OPO signal spectrum has sidebands of nearly equal amplitude. Near threshold we find substantial 3.66 GHz AM throughout the pulse, but increased pump energy reduces modulation, and AM occurs only on the leading edge of the pulse. Figure 2(a) illustrates this behavior, and predictions by our numerical OPO model[1, 2] in Fig. 2(b) are in good qualitative agreement.

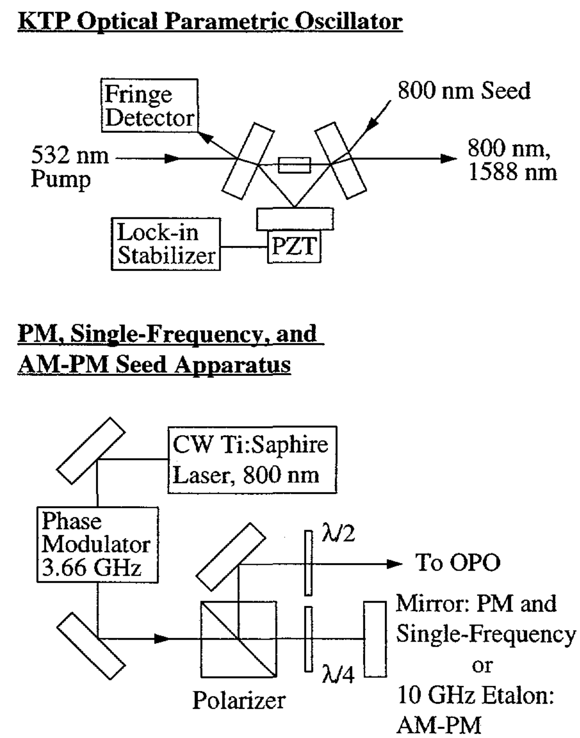


Fig. 1. Diagram of the experimental apparatus.

## Second harmonic efficiency

Figure 2(a) shows a typical signal time profile for *unseeded* operation which exhibits almost no 3.66 GHz AM. This measurement is insensitive to higher frequencies but suggests the unseeded OPO produces PM signal and idler light. To determine if AM is present at higher frequencies, we compared second harmonic generation (SHG) efficiency of the signal wave for unseeded and single-frequency seeded operation. The SHG efficiency, defined as the energy at 400 nm divided by the time integral of the square of the pulse envelope at 800 nm, is the same for unseeded and seeded single-mode operation within the 3% accuracy of the measurement. This is compared with a 60%–70% enhancement expected for $\sim 10$ OPO modes with random phase and amplitude.

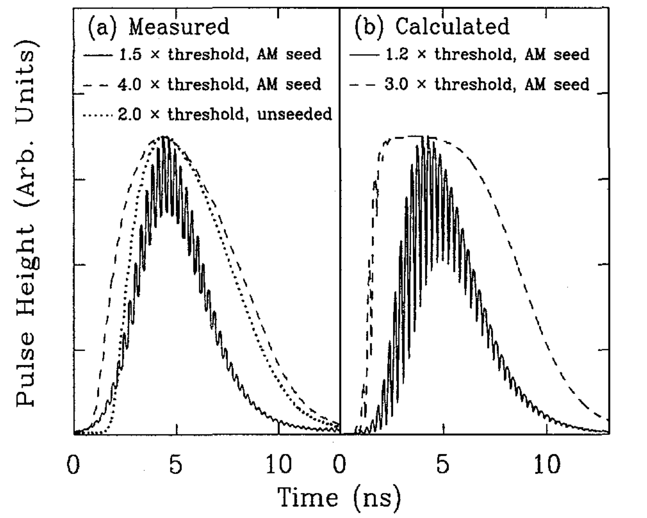


Fig. 2. Temporal pulse profiles. (a) Measured with 3.2 GHz bandwidth detection system, and (b) calculated. Profiles are normalized to have equal peak heights.

## Sum-frequency mixing of signal and idler

We measured the 532 nm spectrum and mixing efficiency for sum-frequency mixing of the signal and idler with various time delays between the signal and idler pulses. If the signal and idler are purely PM with phases

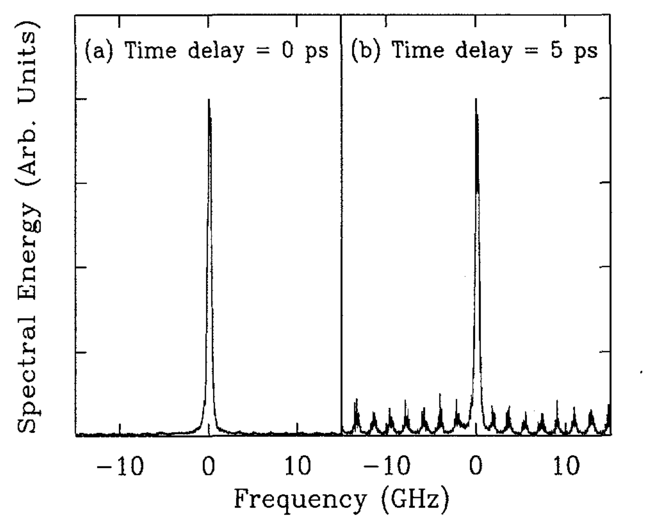


Fig. 3. Scanning Fabry-Perot étalon spectrum of 532 nm light produced by sum-frequency mixing the signal and idler for unseeded operation. The étalon free spectral range of $\sim 40$ GHz is less than the unseeded OPO linewidth.

$\phi_{\mathrm{signal}}(t) = -\phi_{\mathrm{idler}}(t)$, they should sum to produce 532 nm light without PM or AM at zero delay. For nonzero delay, the spectrum should broaden because the signal and idler phases would no longer exactly cancel. If the signal or idler had AM in addition to PM, sidebands with amplitudes $\sim 10\%$ of the carrier would appear on the 532 nm light at zero delay. In addition, if there was time correlation between AM on the signal and idler waves, mixing efficiency should maximize at zero delay. As the delay was stepped through zero, we found no change in the unseeded mixing efficiency within the 2% error of the measurement, indicating no significant correlated AM of the signal and idler. Figure 3 shows the unseeded spectrum for delays of 0 and 5 ps. At zero delay the 532 nm light is nearly monochromatic, also indicating suppressed AM.

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## References


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[2] A. V. Smith W. J. Alford, T. D. Raymond, and M. S. Bowers, J. Opt. Soc. Am. B **12**, 2253-2267 (1995).

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