Tendency of nanosecond optical parametric oscillators to produce purely phase-modulated light

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Received May 7, 1996

We show 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 under a variety of conditions, including both seeded and unseeded operation. © 1996 Optical Society of America

Nanosecond optical parametric oscillators (OPO's) typically oscillate on several longitudinal modes unless they are frequency narrowed by intracavity elements or by injection seeding with narrow-bandwidth light. Linewidths without such narrowing are comparable to the acceptance bandwidth of the nonlinear crystal and can vary from a few to hundreds of wave numbers.[1] Unseeded oscillation builds from quantum fluctuations[2] in the signal and idler fields, so the start-up light for each pulse consists of several longitudinal modes with random amplitudes and phases. This start-up light has both phase modulation (PM) and amplitude modulation (AM). We present evidence here that the longitudinal modes of a nanosecond OPO pumped by temporally smooth pulses from a single-longitudinal-mode laser assume phase relationships that minimize AM, creating signal and idler light that is nearly purely PM.

Such suppression of AM is apparently caused by the combination of zero gain-storage time, high net parametric gain, saturation of the gain from mixing of the signal and the idler to create new pump light, and fresh undepleted pump light on each pass through the OPO cavity. For example, consider the simplified case of an OPO that resonates only the signal wave, seeded on two adjacent cavity modes. This single-sideband seed light has both AM and PM with the modulation period equal to the round-trip time of the cavity. Early in the amplification process, the light in the cavity is a replica of the seed light and interferes constructively with the seed light. The phase of the seed light is unmodified by amplification in the cavity because the idler wave assumes a modulation phase $\phi_{\mathrm{idler}}(t)$ opposite that of the seed modulation phase $\phi_{\mathrm{signal}}(t)$, while linear amplification maintains the AM. However, as the signal energy approaches $\sim$1% of the pump energy (i.e., the oscillation threshold), the amplitudes apparently clamp at a value that depends only on the instantaneous pump level. The maxima in the AM light reach the clamped level first, but the minima quickly catch up, removing the AM but retaining the PM. A similar process must describe unseeded operation; the light fluctuates in both phase and amplitude but the OPO removes the AM while maintaining the PM. We find experimentally that the clamped level is the same for seeded or unseeded operation.

When viewed in the frequency domain, the transformation from two-mode seed to PM output requires the creation of new frequencies, implying strong nonlinear mixing or coupling of the modes. The two signal modes, separated by $\Delta\omega$, and the two idler modes, also separated by $\Delta\omega$, mix to create sidebands on the pump at $\pm\Delta\omega$. These pump sidebands then mix with the original signal and idler to create new signal and idler frequencies. Iteration of this process creates the set of frequencies required for phase modulation. The OPO amplification process then adjusts the phases and the amplitudes of the signal and the idler modes to produce pure PM. In contrast, mixing processes in lasers are usually weak, so the modes are weakly coupled and laser amplification does not adjust the phases and amplitudes of the modes sufficiently to produce PM light. The weak frequency mixing in lasers accounts for the severe AM characteristic of broadband laser light. For example, seeding a Nd:YAG laser on two modes results in nearly pure two-mode output,[3] retaining the strong AM of the seed light.

A direct demonstration of AM suppression in a broadband OPO would require detection bandwidths greater than those available, so we report several less-direct measurements, including efficiency of nonlinear mixing for the signal and idler waves, comparisons of unseeded operation with seeding by single-frequency and modulated light, various spectral studies, and numerical modeling. The experimental apparatus is shown in Fig. 1. The OPO is pumped by single-longitudinal-mode temporally smooth 7-ns-duration (FWHM) 532-nm pulses with a 0.6-mm-diameter (FWHM) Gaussian spatial profile. A cw Ti:sapphire laser seeds the OPO at the 800-nm signal wavelength, and a phase modulator can impose PM on the seed at the 3.66-GHz mode spacing of the OPO cavity. The singly resonant ring cavity has an $R = 0.84$ output coupler and is locked to the signal wave carrier. The cavity contains a 10-mm-long KTP crystal cut at $\theta = 50^\circ$ and $\phi = 0^\circ$, and the unseeded OPO bandwidth is $\sim 2\ \mathrm{cm}^{-1}$. Spectra of the signal and the pump are measured with a high-finesse (> 50) Fabry–Perot étalon with adjustable free spectral range. Pulse time profiles are measured by a Hamamatsu Model R1328U-01 phototube and a Tektronix SCD5000 transient digitizer, giving a combined 3-dB bandwidth of $\sim$3.2 GHz. The attenuation at 3.66 GHz reduces

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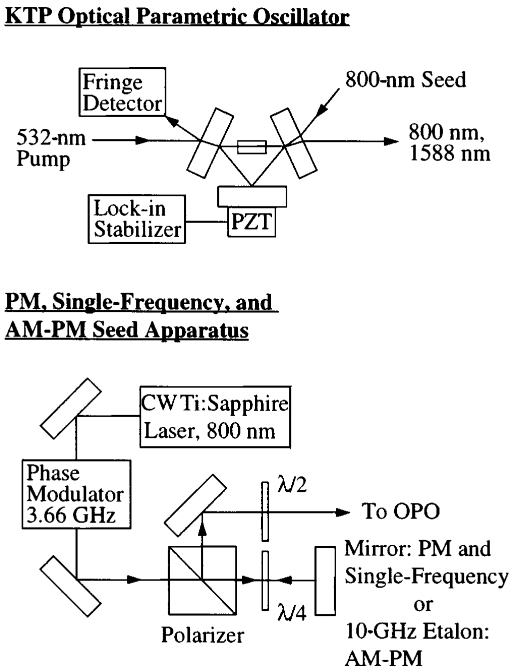

Fig. 1. Diagram of the experimental apparatus: PZT, piezoelectric transducer; $\lambda/2$, half-wave plate; $\lambda/4$, quarter-wave plate. Details of the experiment are given in the text.

measured AM to approximately half its actual value, and frequencies at higher integral multiples of the OPO mode spacing are not observable.

The first evidence that OPO's have an affinity for pure PM is the response to seeding with AM light. To demonstrate this, the 800-nm signal is phase modulated at 3.66 GHz with a modulation index of 0.75, then reflected off a Fabry–Perot étalon with a finesse of 30 and a free spectral range of 10 GHz. The signal wavelength is tuned so that the étalon transmits one PM sideband and reflects light having a combined AM–PM spectrum with unbalanced sidebands. Systematically varying the pump energy from threshold to ~4 times threshold, we find that near threshold there is substantial 3.66-GHz AM that persists throughout the pulse, but as the pump energy increases, the modulation diminishes and occurs only on the leading edge of the pulse. Modulation nearly disappears for pump energies $\gtrsim$3 times threshold. At these high pump energies the signal wave spectrum has sidebands with the reduced but nearly equal amplitudes characteristic of pure PM but with a smaller modulation index than the seed. The AM-seeded signal pulse time profiles in Fig. 2(a) demonstrate diminishing AM with increasing pump, and predictions by our numerical OPO model in Fig. 2(b) are in good qualitative agreement. This model numerically integrates the mixing equations for multilongitudinal-mode plane waves, using realistic OPO physical parameters, and is a modified version of a model used earlier[4,5] to predict successfully thresholds and spectral properties of similar OPO's. We conclude from the time profiles of our experiment and model that this particular OPO prefers PM operation and will convert AM seed light to PM output light. Further, the tendency toward PM grows with increasing pump energy.

Such conversion of AM seed light to PM light poses the question of whether the OPO will produce PM light when unseeded. In Fig. 2(a) we show a typical signal time profile for unseeded operation that has almost no modulation at 3.66 GHz. This measurement, though it is not sensitive to higher frequency modulation, suggests that even the unseeded OPO produces PM signal and idler light. To search for AM at the unobservable higher frequencies, we compared the efficiency of second-harmonic generation of the signal wave for unseeded and single-frequency seeded operation. This is a valid test since it is well known that frequency doubling is more efficient for AM light than for PM light.[6] In fact, light with many modes of random amplitude and phase doubles twice as efficiently as single-mode or PM light in the limit of low conversion. We used a 2-mm-thick crystal of β-barium borate (BBO) as the doubling crystal. The short crystal length ensures insignificant depletion of the signal wave and gives an acceptance bandwidth of 40 cm^{-1}, much greater than the ~2-cm^{-1} signal bandwidth. Doubling efficiency, defined as the energy at 400 nm divided by the integral of the square of the pulse envelope at 800 nm, was the same for unseeded and seeded single-mode operation within the 3% accuracy of the measurement. Further, there was little pulse-to-pulse variation in either case. This is to be compared with a 60–70% enhancement accompanied by large pulse-to-pulse variation expected for ~10 OPO modes with random amplitude and phase. To validate the doubling technique, we seeded the OPO with pure PM light, reflected the output signal light off an étalon to produce AM, and found that the doubling efficiency increased by 16%, in reasonable agreement with an expected enhancement of ~25%.

We next examined the spectrum of 532-nm light created by sum-frequency mixing of the signal and the idler. We introduced a variable time delay between the signal and the idler and mixed them in a 7-mm-long Type I BBO crystal. The acceptance bandwidth for this process is 30 cm^{-1}. If the signal and the idler were both purely PM, we would expect the modulation phases to satisfy $\phi_{\text{signal}}(t) = -\phi_{\text{idler}}(t)$. For

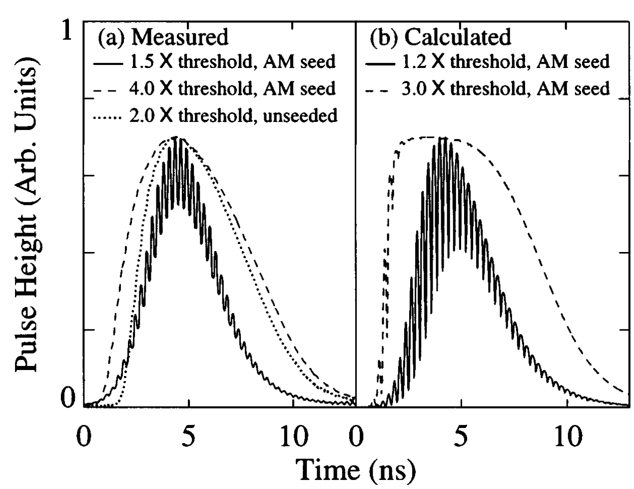

Fig. 2. Signal pulse time profiles. Profiles in (a) were measured with a 3.2-GHz bandwidth detection system. Profiles are normalized to have equal peak heights.

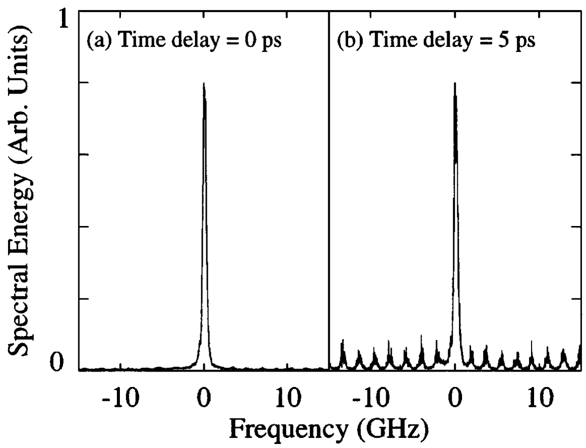

Fig. 3. Scanning Fabry–Perot étalon spectrum of 532-nm light produced by sum-frequency mixing of the signal and the idler for unseeded operation. The étalon free spectral range of ~40 GHz is less than the unseeded OPO linewidth.

zero delay, these phases would cancel in mixing so the generated 532-nm light would have neither PM nor AM. For increasing delays, the spectrum would broaden because the phases of the signal and the idler would no longer exactly cancel. If the signal or the idler had AM in addition to PM, there would be AM sidebands on the 532-nm light at zero delay, even though the signal and idler phases should still be equal and opposite. Numerical simulations of sum-frequency mixing with fields of random phase and amplitude indicate that, if the AM of the random seed light were not suppressed, several 532-nm sidebands with strengths of approximately 10% of the carrier would be expected. Additionally, any AM of the signal and idler waves would likely be correlated in time, so mixing efficiency should maximize at zero delay. We studied the spectrum and the mixing efficiency as the delay was stepped through zero and found no change in mixing efficiency at zero delay within the ~3% measurement error, for either PM-seeded or -unseeded operation, indicating that there is no significant time-correlated AM of signal and idler. Spectra of the 532-nm light shown in Fig. 3 for unseeded operation support these observations. For zero delay, the 532-nm light is nearly monochromatic, indicating strong suppression of AM. For delays of 5 ps or greater, the light is noticeably polychromatic, with many sidebands that increase in strength with increasing delay.

As a brief summary of evidence that our OPO produces nearly pure PM signal and idler light when pumped well above the oscillation threshold, recall that we have shown that there is almost no AM of the signal light at the 3.66-GHz longitudinal mode spacing for either AM-seeded or unseeded operation. Further, the doubling efficiency of the signal wave is independent of whether or how the OPO is seeded. The spectrum of light generated by sum-frequency mixing of the signal and the idler is monochromatic for seeded and unseeded operation, and the mixing efficiency is not sensitive to the signal-to-idler time delay. Additionally, a numerical model of OPO operation that has been validated in previous research predicts that the OPO will convert AM seed light to PM light and that the conversion is more thorough as the pump energy increases, in accord with laboratory observation.

To test the generality of the effect, we applied our numerical model to various OPO designs, checking whether single-sideband seeding produces PM output. We find that the AM-to-PM conversion is quite general and occurs when idler feedback is nonzero, as in a doubly resonant OPO, although AM on the leading edge of the pulse persists later into the pulse than for singly resonant OPO's. Suppression of AM also occurs for a wide range of output coupler reflectivities in singly resonant OPO's and for a wide range of OPO cavity lengths and pump pulse durations (5–50 ns).

This propensity for pure PM operation has some practical implications. It means that frequency doubling of the signal or idler has the same efficiency for seeded or unseeded operation, assuming that the doubling crystal has an acceptance bandwidth larger than signal bandwidth. It also indicates that OPO's might be well suited for PM spectroscopy applications.[7,8] The OPO could be seeded with PM light with significant residual AM, or even with AM light, and still produce high-quality PM light. The tendency for PM operation can enhance some applications such as difference-frequency mixing of the signal and idler to extend the IR tuning range of the OPO. For PM-seeded operation, the modulation index of light created by sum- or difference-frequency mixing of the signal and the idler can be continually adjusted from 0 to 2 times the modulation index of the seed by adjustment of the time delay between the signal and idler pulses. For unseeded operation, the difference-frequency mixed light will be multimode but smooth in time, provided that the crystal acceptance bandwidth is much greater than the bandwidth of the signal or the idler. Finally, the lack of high-intensity spikes from AM mitigates optical damage in the OPO and associated optics.

This research is supported by the U.S. Department of Energy under contract DE-AC04-94AL85000. We thank G. A. Hebner for advice on high-frequency modulation and detection and G. M. Loubriel for the use of the transient digitizer.

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