Multiple conversion and optical limiting in a subharmonic-pumped parametric oscillator

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We demonstrate that multiple coexisting frequency-conversion processes can occur in an externally resonant second-harmonic generator under suitable conditions. Besides the generation of signal and idler waves by subharmonic-pumped parametric oscillation, sum-frequency mixing among the resonant subharmonic (1064-nm), signal, and idler waves was observed, leading to additional emission wavelengths around the harmonic wavelength (532 nm). The output waves both exhibit high frequency stability, with as long as 4 h of mode-hop-free parametric oscillation, and are continuously tunable over 2 GHz. Near degeneracy the parametric oscillator operates as an optical limiter for the harmonic wave.

The combination of subsequent nonlinear optical frequency-conversion processes can be used for generating broadly tunable continuous-wave laser light. In various experiments external resonant frequency doubling has been used to generate visible pump light for continuous-wave optical parametric oscillators (OPO's) emitting in the near- or mid-infrared spectral range. Extending the tunable OPO emission into the visible could in principle be achieved by doubling the OPO output. The subharmonic-pumped parametric oscillator (SPO) avoids the complexity of distinct cascaded resonant nonlinear devices by using multiple frequency conversions within a single cavity. The SPO is a combination of a resonant frequency doubler and a doubly resonant parametric oscillator, with the pump wave not being resonated. SPO was first observed with a monolithic resonator. It was shown that an SPO has the intrinsic feature of generating frequency-stable output, a consequence of making the cavity resonant for the subharmonic pump wave. A theoretical description of the SPO was developed, and squeezing in the harmonic wave was studied.

In this Letter we investigate several new properties of the SPO with a semimonolithic cavity implementation. A central task was to achieve both frequency stability and continuous tunability. In doubly resonant OPO's with external pump sources this has been difficult to achieve. Although 3 h of mode-hop-free operation has been the longest time for doubly resonant OPO's reported so far, we show that in a SPO single-frequency operation over many hours, as well as continuous tuning, can be obtained in a simple and reliable fashion with a single semimonolithic cavity. We also demonstrate that high overall conversion efficiencies can be obtained with such a device.

While the SPO is based on a twofold frequency conversion process in a single cavity, we have found that even threefold conversion can occur in the same cavity, where subharmonic-pumped parametric oscillation is followed by sum frequency generation [Fig. 1(a)]. Moreover, we show an optical limiter effect for the generated second-harmonic power.

A schematic of our setup is shown in Fig. 1(b). We use a diode-pumped monolithic Nd:YAG ring laser with a single-frequency output power of 1.64 W at 1064 nm and a linewidth of 1 kHz. The output frequency can be slowly tuned over a range of 10 GHz by control of the laser crystal temperature, and fast tuning over a range of 100 MHz is possible by application of stress to the crystal with a piezo. A Faraday isolator is used to prevent backreflection from the standing wave cavity to the laser.

The semimonolithic resonator (see also Ref. 8) consists of a 7.5-mm-long MgO:LiNbO₃ crystal and an external mirror separated by 24 mm. One endface of the crystal is polished with a 10-mm radius of curvature and coated with a high reflector for 1064 and 532 nm. The other endface is flat and antireflection coated for both wavelengths. A 25-mm radius-of-curvature mirror with a transmittivity of T = 2.5% for 1064 nm and 90% for 532 nm serves as input coupler for the injected laser light and as output coupler for the generated second-harmonic and signal–idler output waves. The mirror is mounted on a piezoelectric actuator to lock the cavity length on resonance with the laser frequency. A simple and stable resonance locking scheme is obtained by a modified frequency-modulation technique, where the cavity length is electro-optically modulated.
at 12 MHz by two copper electrodes in contact with the crystal faces perpendicular to the optical axis.

The injected fundamental wave is polarized perpendicularly to the optical axis of the crystal to achieve type I phase matching. The nonresonant second-harmonic wave double passes the cavity to enhance the nonlinear coupling to the fundamental wave. The SPO crystal is heated to close to 118 °C in a temperature-controlled aluminum oven to allow parametric oscillation near the phase-matching peak for second-harmonic generation (SHG). The nonlinear coefficient of the crystal was determined by SHG, $\gamma_{\text{SHG}} = P_{\text{2th}}/P_{\text{r}}^2 = 2.4 \pm 0.3 \text{ kW}^{-1}$. The round-trip power loss in the cavity was determined to be $A = 0.5\%$ by measurement of the finesse of the resonator, with the input coupler replaced by a high reflector. The threshold pump power for subharmonic-pumped oscillation is $P_{\text{th}} = \zeta(A + T)^3/(T\gamma_{\text{SHG}})$, where $\zeta$ is a numerical factor depending on focusing and phase mismatches of the waves in the SHG and parametric processes. For our resonator geometry a minimum value of $\zeta = 0.83$ is predicted, yielding a threshold pump power of 375 mW.

We observed oscillation at subharmonic powers above 390 mW, in agreement with the theoretical prediction. A central characteristic of the SPO is its frequency stability. Fig. 2 shows a typical scanning Fabry–Perot spectrum taken at an input subharmonic power of 1 W and a temperature optimized for maximum SHG efficiency. At this and lower input powers oscillation on a single signal–idler mode pair was observed for as long as 4 h. To our knowledge, this is the longest single-frequency continuous operation time of an OPO to date. The total conversion efficiency to signal (1062.8 nm) plus idler (1065.5 nm) is 20%.

Investigating the temperature-tuning behavior of the SPO, we found that in the temperature range between 118 and 119.5 °C signal and idler were nearly degenerate. Above 119.5 °C oscillation wavelengths of 1047 and 1082 nm were observed. These lie on the cluster curve next to degeneracy. The location of the nearly temperature-independent cluster curves is $\omega_s - \omega = \sqrt{q} \Delta \omega_c$, where $q = 1, 2, \ldots$ is the index of the cluster curve. The spacing $\Delta \omega_c$ can be calculated from the round-trip phase shift $\phi = n(\omega)L_{\text{rt}}/c + \phi_m(\omega)$, where $\phi_m(\omega)$ is a dispersive phase shift of the cavity mirror coatings. We obtain

$$\Delta \omega_c = \left[ \frac{1}{2\pi} \frac{\partial^2 \phi}{\partial \omega^2} \right]^{-1/2},$$

where $n$ is the refractive index and $L_{\text{rt}}$ is the round-trip length within the crystal. The derivatives are taken at the subharmonic frequency $\omega$. The observed cluster spacing of $\Delta \omega_c/2\pi = 4.6 \text{ GHz}$ can be explained assuming $\partial^2 \phi_m/\partial \omega^2 = 3.4 \times 10^{-27} \text{ s}^2$, which is consistent with the narrow reflectance curve of the crystal and mirror coatings. Oscillation on the 1047- and 1082-nm wavelengths remained up to a temperature of 122 °C, above which the available input power was not sufficient to reach threshold owing to a significantly decreased SHG efficiency.

Continuous tuning of the SPO output was obtained by tuning of the laser frequency. As observed with the Fabry–Perot interferometer, the frequencies of signal and idler waves followed the subharmonic (laser) frequency continuously without power loss over a range of 2 GHz, after which a mode hop occurred. The maximum tuning rate is approximately 1 GHz/s. From the tight cavity lock and the power stability of the SPO output frequencies we can infer that the absolute frequency instability is essentially given by that of the laser source, which is 30 MHz over 1 h in the present case.

Additional frequency-conversion processes took place in the cavity at input powers above 500 mW, where we could observe subharmonic-pumped parametric oscillation followed by sum-frequency mixing between the subharmonic wave and the signal–idler waves; see Fig. 1(a). Figures 3(a) and 3(b) show spectrometer measurements near 1064 and 532 nm, respectively. Signal and idler wavelengths were determined at 1062.8 and 1065.5 nm, whereas the sum frequency

![Fig. 2. Fabry–Perot interferometer spectrum of the SPO pumped at a subharmonic power of 1 W. The conversion efficiency to signal plus idler is 20%.

![Fig. 3. Spectrometer measurements of the SPO output at (a) 1064 and (b) 532 nm, respectively. Both spectra are taken at 118.2 °C and a pump power of 900 mW.](image-url)
waves were at 531.8 and 532.5 nm. The total conversion efficiency for the sum-frequency mixing was typically 0.7%. Owing to different wave-vector mismatches in the two sum frequency processes, the powers of the generated waves differ slightly. They exhibit the same long-term power stability as the signal and idler waves. For input powers above 1 W simultaneous oscillation on as many as five signal–idler mode pairs occurred. Accordingly, additional pairs of sum-frequency-generated waves (as many as two) were observed. At these power levels mode hops became frequent, occurring on a time scale of minutes.

Optical limiting (clamping) of the pump wave power in doubly-resonant OPO’s was first discussed by Siegman. More recently it was predicted that this effect can also occur in singly resonant frequency doubling. Here the emission of signal–idler waves represents an additional nonlinear power loss for the harmonic wave, which leads to limiting of its power. We have observed power limiting of the 532-nm harmonic wave when operating at the point of maximum SHG efficiency. Figure 4 shows the simultaneous time traces of the subharmonic input and harmonic output powers while the laser power was changed manually by rotating a half-wave plate in front of the Faraday isolator. At the onset of parametric oscillation power clamping of the harmonic wave occurred, which persisted for subharmonic powers up to 1150 mW. Because increasing the input power heated the crystal, the startup of power limiting shows a steplike behavior. Small variations in the limited harmonic power result from mode hops that are due to thermally induced cavity length changes. Apart from these mode hops the SPO always operated on a single mode pair. The type of limiting observed here is not dependent on achieving perfect mode matching as in usual double-ended parametric oscillators. Thus it may represent a simple way of generating a wave with intensity fluctuations near the shot-noise limit starting from a subharmonic wave with excess noise.

In conclusion, we have demonstrated that the subharmonic-pumped parametric oscillator (SPO) is a unique nonlinear system with technically important features. When a semimonolithic cavity is used, a SPO is the simplest system in which one can observe multiple simultaneous nonlinear optical processes that lead to highly frequency-stable as well as frequency-tunable emission. It therefore is an interesting device for generating narrow-linearband tunable radiation in both the infrared and the visible with an infrared pump source. The robust and reliable stabilization of the SPO cavity uses a single servo loop only, which does not depend on detecting signal or idler radiation. Finally, optical limiting of the generated harmonic wave was shown to occur in degenerate operation of the SPO. Surprising as it may seem, these rich features are exhibited by one of the most common nonlinear devices, the externally singly-resonant frequency doubler.

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References


12. Optical limiting in SPO was independently observed in Ref. 5.