Subharmonic-pumped continuous-wave parametric oscillator

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We have operated a doubly resonant optical parametric oscillator (OPO) whose pump wave is generated in the OPO cavity itself by resonant frequency doubling of an injected subharmonic wave. The subharmonic-pumped oscillator employs a miniature monolithic MgO:LiNbO$_3$ resonator and is pumped by a single-frequency Nd:YAG laser at 1064 nm. The threshold power was 120 mW at 1064 nm, and an efficiency of 7% for the conversion from 1064 to 1063/1065 nm via the nonresonant 532 nm wave was reached at 300 mW infrared input power. Single-frequency operation for up to one-and-a-half hours was observed. *© 1996 American Institute of Physics.* [S0003-6951(96)03824-7]

Continuous-wave optical parametric oscillators have undergone significant developments in the last decade.[1] Many cw OPOs employ pump waves in the visible spectral range, that are frequently generated by externally resonant second-harmonic generation (SHG).[2] While this is a standard technique, the separate frequency doubling stage adds to the complexity of the oscillator. One possible alternative, not yet demonstrated with cw lasers, is to use cascaded frequency conversion in enhancement cavities containing two separate nonlinear media.[3] In this letter, we show an even simpler implementation, consisting in combining the resonant SHG and oscillation processes (here type I) in a single nonlinear medium. Earlier, this concept of subharmonic-pumped parametric oscillator (SPO) had been implemented using SHG with resonant harmonic wave;[4] the present extension to the nonresonant case avoids the complexity of a double frequency lock.

A schematic of a SPO is shown in Fig. 1. Subharmonic (ω), signal (s), and idler (i) waves resonate in a cavity of round-trip loss S and mirror transmission T. Their interaction in a nonlinear medium (length L) is mediated via the intermediary of a nonresonant harmonic wave ($2\omega=\omega_s+\omega_i$) that arises from SHG and that simultaneously drives the parametric generation process. Focusing the discussion on the case of near-degenerate oscillation, $\Delta KL=(k_2-k_i-k_s)L\simeq 0$, near-maximum SHG efficiency, $\Delta kL=(k_2-2k_1)L\simeq 0$, and plane-wave modes, the evolution equations for the electric field envelopes $A(z)$ of subharmonic, harmonic, idler, and signal waves are[5]

$$\frac{dA_1}{dz}=i\frac{\kappa}{2}A_1^*A_2,\quad \frac{dA_2}{dz}=i\frac{\kappa}{2}A_i^2+i\kappa A_iA_s, \tag{1}$$

$$\frac{dA_{i/s}}{dz}=i\frac{\kappa}{2}A_{s/i}^*A_2, \tag{2}$$

where κ is the scaled nonlinear coefficient.

At or below threshold, A_i and A_s are negligible and the nonresonant harmonic field grows linearly along the medium, $A_2(z)=i\kappa A_1(0)^2z/2$, since in a high-finesse cavity ($S+T\ll 1$) the amplitude of the resonant subharmonic wave is nearly constant. Consider now the parametric gain for signal and idler, $\kappa A_2(z)/2$. At threshold, its average over the crystal length L must be equal to $\kappa A_2^{\mathrm{DRO}}/2$, where $A_2^{\mathrm{DRO}}=(S+T)/\kappa L$ is the threshold harmonic amplitude for usual doubly resonant oscillation pumped directly by a harmonic wave. Thus, the output harmonic amplitude at threshold is $A_2(L)=2A_2^{\mathrm{DRO}}$. Under this condition, the subharmonic wave's fractional amplitude loss upon traversing the crystal due to harmonic generation equals that due to passive loss, $\kappa LA_2^{\mathrm{DRO}}/2=(S+T)/2$. This situation is known to occur when the subharmonic input power is such that maximum SHG conversion efficiency, $P_2/P_1=T/(S+T)$, is reached.[6] The SPO threshold follows explicitly, as

$$P_1^{th}=\frac{T+S}{T}P_2=4\frac{T+S}{T}P_2^{\mathrm{DRO}}, \tag{3}$$

where P_2^{DRO} is the power corresponding to A_2^{DRO}. Summarizing, the SPO is a conventional second-harmonic generator for low subharmonic pump power, parametric oscillation setting in, under the above assumptions, once the pump level is increased beyond P_1^{th}, the point of maximum SHG efficiency. For comparison, the threshold of a SPO whose cavity contains two crystals for independent SHG and parametric interactions, is a factor 4 smaller than P_1^{th}.[3]

Turning to the experimental aspects, the SPO employs a 7.5 mm long monolithic standing-wave resonator fabricated from MgO:LiNbO$_3$ with dielectric mirrors deposited directly on the curved endfaces.[7,8] The back coating is nearly com-

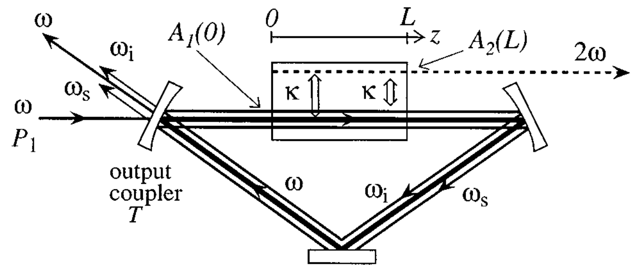

FIG. 1. Principle of the subharmonic-pumped parametric oscillator (SPO). For clarity, a ring cavity with discrete components is shown. A resonant subharmonic wave (full line) generates a harmonic wave (2ω, dashed line) that in turn generates resonant signal ω_s and idler ω_i waves (thin full lines). The harmonic wave is not resonant. T is the mirror transmission for ω, ω_s, and ω_i.

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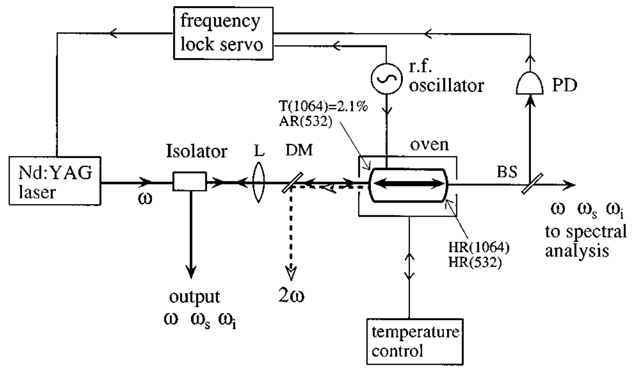

FIG. 2. Layout of the experiment. L, mode matching optics; DM, dichroic mirror; BS, beam splitter; PD, radio frequency photodetector; HR, high reflector, AR, antireflective coating. The small transmission of the infrared waves through the back reflector of the resonator is used for generation of the lock error signal and for spectral analysis.

pletely reflective for wavelengths near 1064 nm and at 532 nm, the front coating has $T=2.1\%$ around 1064 nm and is antireflective for 532 nm. The resonator supports TEM_{00} modes with a waist of 27 μm at 1064 nm. Cavity losses S are about 0.3%. Pumped by 532 nm, the resonator has a threshold $P_2^{\mathrm{DRO}}=29$ mW for conventional doubly resonant parametric oscillation.[8]

The setup for SPO operation is shown in Fig. 2. The subharmonic wave is provided by a diode-pumped Nd:YAG laser with single-frequency output ω near 1064 nm. The laser frequency is actively stabilized to a cavity resonance by means of a servo system employing a frequency-modulation technique.[7,9] The SPO is located in a temperature-stabilized oven heated to about 110 °C to permit operation in the vicinity of the SHG phase-matching peak. The SHG conversion efficiency from 1064 to 532 nm, with the oven temperature optimized at each pump power, has already been reported.[7] It reaches a maximum of 82% for a 1064 nm pump power of ~100 mW. Oscillation occurred above 120 mW, accompanied by a clear reduction in SHG efficiency. The threshold value is in fair agreement with the plane-wave SPO threshold power predicted by Eq. (3). Typical power conversion efficiencies to signal plus idler were around 7% for input powers twice above threshold. The SPO threshold increases as the crystal temperature is changed from the phase-matching peak due to a reduction in SHG efficiency. For the available infrared power, oscillation was therefore only observed in a 2 K interval around the peak.

In a SPO, the subharmonic, signal, and idler waves all resonate in a common cavity. Two notable consequences result. First, under a perturbation or change in cavity optical path length, the signal and idler cavity mode frequencies shift. To allow the signal and idler oscillation frequencies to shift by the same amount, the pump frequency must shift accordingly. This cluster condition[10] is automatically satisfied when signal and idler frequencies are near-degenerate, since the subharmonic is locked to a cavity mode that shifts by the same amount and therefore the required frequency shift is transferred to the harmonic. Excellent frequency stability of the SPO output was indeed observed when pumped at less than 200 mW power. Mode hops occurred infrequently, with single-frequency operation lasting typically for more than 1 h.

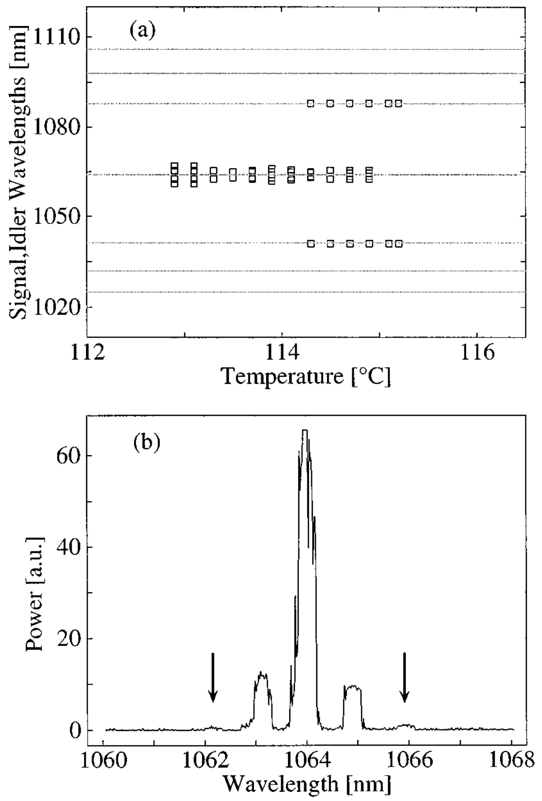

FIG. 3. (a) Output wavelengths generated by the SPO by temperature tuning. The horizontal lines are calculated cluster curves at multiples of $\Delta\nu=6.2$ THz. (b) Near-degenerate output spectrum of the SPO under strong pumping (300 mW), showing oscillation on two signal/idler pairs simultaneously. The central peak is the pump wave. Peak widths are due to the spectrometer resolution.

Second, the harmonic frequency is not an independent parameter with a continuous tuning range. As the subharmonic frequency can take on only discrete values corresponding to cavity frequencies, the allowed signal/idler frequencies are predicted, under simplifying assumptions, to be offset from degeneracy by multiples of $\Delta\nu=[c/2\pi L_{rt}(\omega\partial^2 n/\partial\omega^2+2\partial n/\partial\omega)]^{1/2}$ where n is the refractive index and the derivatives are taken at the degeneracy (subharmonic) frequency ω^4 and L_{rt} is the round-trip length of the monolithic resonator. The actual oscillation frequencies within this set depend on the crystal temperature through the condition of small wave vector mismatch ΔKL. Figure 3(a) displays the observed oscillation wavelengths. The spacing of the pair at 1087/1041 nm agrees with the calculated value of $\Delta\nu=6.2$ THz.

In addition, oscillation also occurred within a few nm of the pump wavelength, Fig. 3(b). Just visible in the spectrum are additional output wavelengths, appearing at high pump powers. We have observed stable simultaneous oscillations of up to 10 signal/idler pairs, with mode hops occurring on a time scale of minutes. These effects go beyond the four-mode model discussed previously, and may be explained by a sequence of cascaded nonlinear interactions. For example, the two-step interaction leading to the SPO can be followed by generation of the sum frequency $\omega+\omega_{s/i}$ or of the harmonics of the main signal/idler frequencies, $2\omega_{s/i}$ and subsequent difference frequency mixing with $\omega_{i/s}$ or ω, respectively, to produce difference frequencies $\omega \pm (\omega_s - \omega_i)$. These higher-order effects are only expected to be important when $\Delta kL \simeq 0,\ \Delta KL \simeq 0$.

In conclusion, we have demonstrated a novel cw parametric oscillator that combines SHG and parametric generation in a single crystal. The resulting device is simple, and by its very nature, generates frequency-stable signal/idler waves. The ability to generate a signal/idler pair whose frequency difference depends on cavity length may be useful for frequency metrology purposes, particularly with a variable cavity-length design. We have also operated a SPO using a similar monolithic resonator with lower input coupler transmission of $T = 0.4\%$ and losses comparable to those above. This device had a lower SPO threshold of 40 mW. Parametric oscillation in second-harmonic generation for pump powers above the point of optimum SHG efficiency is also of relevance for quantum optics. It is expected to influence the quantum noise suppression of the harmonic wave obtained in frequency doubling .[6,11] Finally, the SPO may represent a practical source for the generation of quantum-correlated signal/idler waves.[12]

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