

# Bichromatic frequency conversion in potassium niobate

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Two frequency components of an IR laser beam near 980 nm are simultaneously coupled into two adjacent longitudinal modes of a passive ring resonator. A potassium niobate crystal inside the resonator converts the circulating IR light into coherent blue radiation. The total conversion efficiency is enhanced by a factor of 1.4 compared with that of conventional single-mode intracavity second-harmonic generation with the same circulating total power, and we obtain a total output power of 560 mW from 780-mW IR light incident upon the cavity. The spectra of the generated blue radiation and the circulating IR light contain a number of equidistant frequency components that are due to consecutive sum- and difference-frequency mixing. © 1998 Optical Society of America

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Optical frequency conversion of IR radiation in nonlinear crystals has developed into a powerful tool for generating intense blue light with convenient solid-state laser sources. Conversion efficiencies of 50% or more can be achieved if the crystal is placed inside a passive buildup cavity that resonantly enhances the fundamental light.<sup>1</sup> The fundamental IR radiation can be provided by high-power semiconductor lasers<sup>2</sup> or, more traditionally, by a Ti:sapphire laser.<sup>3</sup> Ti:sapphire lasers are typically pumped by expensive argon-ion lasers; however, frequency-doubled Nd:YAG lasers with as much as 10 W of output power are already commercially available. In combination with a miniature dual-mode Ti:sapphire laser,<sup>4</sup> a compact and tunable all-solid-state blue-light source with more than 0.5 W of output power is conceivable.

Nonlinear conversion efficiency can be improved if a dual-mode laser is used that simultaneously emits two frequency components of equal power. Both components are coupled into adjacent longitudinal modes of the buildup cavity, and inside the crystal the total circulating power varies owing to the interference between the two modes. During constructive interference the harmonic wave is generated with an enhanced efficiency because of its quadratic dependence on the fundamental power. This effect increases the average power conversion, as in the case of frequency doubling of mode-locked pulse trains. The power inside the crystal can be written as  $P(t) = P_0[2 \sin(\pi \nu t)]^2$ , where  $P_0$  and  $\nu$  denote the power per mode and the difference frequency between the two modes, respectively. This equation leads to a time-dependent harmonic light power  $P_{\text{sh}}^{(\text{dual})}(t) = \eta P(t)^2$  with a temporal average value of  $P_{\text{sh}}^{(\text{dual})} = \langle \eta P_0^2 [2 \sin(\pi \nu t)]^4 \rangle = 6\eta P_0^2$ . Here  $\eta$  denotes the nonlinear conversion coefficient. Compared with the output in the case in which the total fundamental power is concentrated in only one mode,  $P_{\text{sh}}^{(\text{single})} = \eta(2P_0)^2$ , the converted output is enhanced by a factor  $P_{\text{sh}}^{(\text{dual})}/P_{\text{sh}}^{(\text{single})} = 6/4 = 1.5$ . In the frequency domain this enhancement factor is explained by the fact that the two fundamental frequency components gener-

ate two second-harmonic components and a sum component. As we show below, standard theory predicts that the power of the sum component alone equals that of the equivalent single-mode doubler. The two harmonic components are expected to be of equal strength and four times weaker than the same component, which results in a total output power that is consistent with the above-derived factor of 1.5. In this Letter we report on bichromatic frequency conversion with a potassium niobate crystal at a fundamental wavelength near 980 nm. The observed ratio between the sum component and the two harmonic components deviates from the expected value of 4:1 for high intensities. Further, the spectra of the generated blue light and the circulating IR light show additional frequency components that are due to consecutive sum- and difference-frequency mixing.

The two frequency components of a miniature dual-mode Ti:sapphire laser<sup>4</sup> with equal intensity and a frequency separation of 1.2 GHz are coupled into two adjacent modes of a passive bowtie-type ring resonator. A 7.5-mm-long potassium niobate crystal is placed inside the resonator halfway between its two curved mirrors (radius of curvature, 25 mm). The crystal facets are cut perpendicular to the  $b$  axis and antireflection coated for IR and blue light near 980 and 490 nm, respectively. To maintain optimum phase matching the crystal temperature is stabilized with a Peltier cooler and an electronic servo loop to 16 °C. The geometric path length of the laser beam between the curved mirrors is 30.7 mm, and the path length via the two plane mirrors is 196 mm. The incidence angle on the curved mirrors is 10°. This geometry leads to a circular focus inside the crystal with a waist of 25  $\mu\text{m}$ , according to the condition for optimum conversion efficiency.<sup>5</sup> The plane input coupler transmits 6.2%. The generated blue light leaves the resonator through one of the curved mirrors (85% transmission at 490 nm). The resonator is tuned by a piezo translator onto which one of the two plane mirrors is cemented. An electronic servo loop keeps the cavity in resonance with the incident light. The error signal is generated by analysis

of the polarization of the light reflected at the input coupler.<sup>6</sup> The circulating IR power is monitored behind one of the curved mirrors (0.041% transmission). One determines the passive losses of the resonator by detuning the crystal temperature from optimum phase matching and monitoring the ratio between the incident and the circulating light power. The observed enhancement factor of 24 corresponds to 4% losses. The free spectral range of the resonator is matched to the mode separation of the laser by variation of the position of one of the plane mirrors until the transmission on resonance is maximized. At optimum phase matching the losses are dominated by nonlinear conversion. Then, the enhancement factor decreases to  $\sim 7$ , and 13% of the incident light is reflected at the input coupler.

From 780-mW incident IR light we obtain as much as 2.4 W of circulating power in each of the two modes and a total blue output power of 560 mW (behind the crystal; Fig. 1). Figure 2 shows the spectrum of the blue light as recorded with a confocal Fabry–Perot spectrum analyzer (1.5-GHz free spectral range; finesse, 200). Besides the sum and the second-harmonic components, four additional components appear 1.2 and 2.4 GHz above and below the two second-harmonic frequencies. Spectra were taken for various IR power levels. For each spectrum the crystal temperature was optimized for minimum circulating fundamental power, which indicates maximum conversion. The intensity ratio between the two harmonic components and the sum component turned out to be power dependent and is plotted in Fig. 3. The spectrum of the circulating IR light (Fig. 4) was recorded in the transmitted light behind one of the resonator's curved mirrors with a confocal Fabry–Perot spectrum analyzer (3-GHz free spectral range; finesse, 100). Besides the resonator modes, which are driven by the two laser modes, two additional longitudinal modes are excited and contain as much as 10 mW of circulating power. The power dependence of the first harmonic and the fundamental sidebands is shown in Fig. 5.

We start the discussion with a set of differential equations that describe the amplitudes of the Gaussian field modes for the harmonic and the sum components<sup>7</sup>:

$$\frac{da_{sh}}{dz} = \frac{\omega}{nc} \chi^{(2)} a_f^2 \frac{\exp(i\Delta kz)}{1 + i2z/b} \left( 1 - 2 \frac{a_{fs}}{a_f} \right),$$

$$\frac{da_{sum}}{dz} = 2 \frac{\omega}{nc} \chi^{(2)} a_f^2 \frac{\exp(i\Delta kz)}{1 + i2z/b} \left[ 1 + \left( \frac{a_{fs}}{a_f} \right)^2 \right].$$

Here  $b$  denotes the confocal parameter of the fundamental mode and  $\Delta k$  is the phase mismatch between the IR and the blue waves accumulated along the crystal. The second term of the first equation ( $2a_{fs}/a_f$ ) describes the frequency mixing between the fundamental wave and the fundamental sideband, which together generate a polarization wave at a harmonic frequency. Similarly, the last term in the second equation describes the sum mixing between the two fundamental sidebands. We neglect the small power

drop of the fundamental waves along the crystal owing to conversion losses and also assume a constant field amplitude for the fundamental sidebands, since they are resonantly enhanced and recycled inside the cavity. The two conversion processes of the first equation are expected to interfere destructively, provided that the fundamental sidebands are generated by difference-frequency mixing between a fundamental and a harmonic component and that the harmonic components result from second-harmonic generation of a fundamental wave. The above equations are evaluated according to the standard treatment,<sup>7</sup> yielding

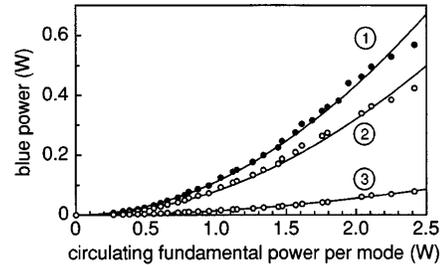


Fig. 1. ① Total blue output power versus fundamental power circulating inside the resonator. ②, ③, Power of the sum component and in one of the harmonic components, respectively. Solid curves, theoretical expectations according to a conversion coefficient  $\eta$  of 2.0%/W.

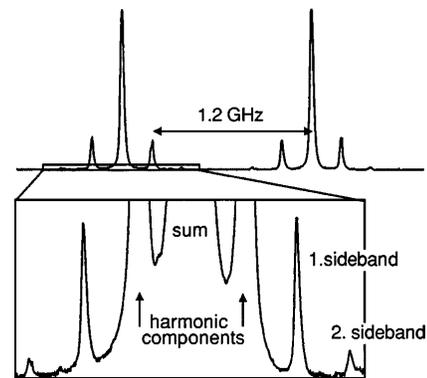


Fig. 2. Spectrum of the generated blue light as recorded with an optical spectrum analyzer with a free spectral range of 1.5 GHz.

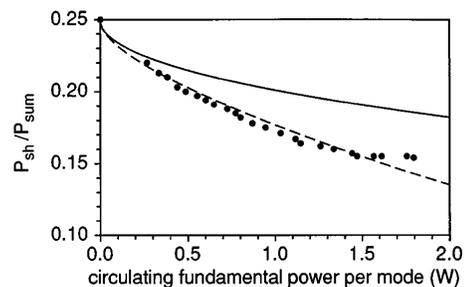


Fig. 3. Power ratio between one of the second-harmonic components and the sum component in the spectrum of the generated blue light. The solid curve indicates the expected ratio if only  $\chi^{(2)}$  processes are taken into account. For the dashed curve see the text.

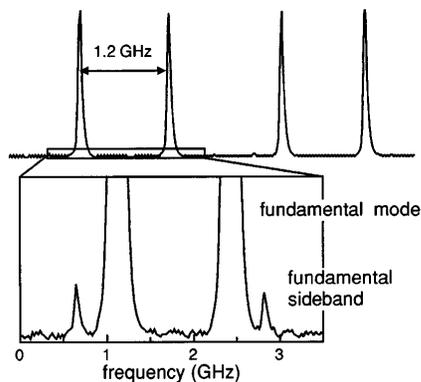


Fig. 4. Spectrum of the fundamental light circulating inside the resonator. In addition to the two injected fundamental modes, two sidebands appear owing to difference-frequency mixing between one fundamental mode and one of the two blue harmonic components.

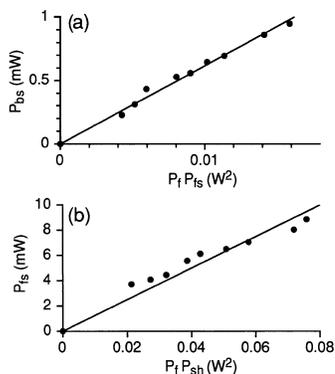


Fig. 5. Power of (a) the first blue sideband and (b) the fundamental sideband. The blue sideband power can be described by  $P_{bs} = 4\eta P_{fs} P_f$ . A fit to the experimental data yields  $\eta = 1.5\%/W$ , which is somewhat below the values derived in Fig. 1.

expressions for the power of the harmonic components,  $P_{sh} = \eta P_f^2 [1 - 2(P_{fs}/P_f)^{1/2}]^2$ , and the sum component,  $P_{sum} = 4\eta P_f^2 (1 + P_{fs}/P_f)^2$ . Here  $\eta$  denotes the conversion coefficient, which for our crystal amounts to a theoretical value of  $2.4\%/W$ .<sup>8</sup> A fit of the above equations to the experimental data yields  $\eta = 2\%/W$  (Fig. 1). The total blue output can be described by an effective conversion efficiency  $P_{tot} = \eta_{eff} (2P_f^2)$ , with  $\eta_{eff} = 2.7\%/W$ . Apparently, the splitting of the fundamental power into two frequencies improves the total conversion efficiency by a factor of 1.4. The deviation from the expected factor of 1.5 reflects the conversion losses of the harmonic components owing to the generation of the fundamental sidebands.

For higher power the observed data deviate from the theoretical curves (Fig. 1), which can clearly be seen if the ratio  $P_{sh}/P_{sum}$  is plotted versus the circu-

lating fundamental power (Fig. 3). The strong suppression of the harmonic components suggests the presence of an additional optical process that discriminates between the harmonic and the sum components. Third-order nonlinear processes such as four-wave mixing and two-photon absorption of an IR and a blue photon can be considered. A preliminary analysis in the plane-wave approximation supports this notion (dashed curve in Fig. 3), but only when it is assumed that there is an extraordinarily and probably unrealistically large third-order nonlinear susceptibility of the order of  $\chi^{(3)} \approx 10^{-17} \text{ m}^2/\text{V}^2$ .

The power of the fundamental sideband is resonantly enhanced according to  $P_{fs} = A\eta P_{sh} P_f$ , where  $A = (1 - R_m^{1/2})^{-2}$  and  $1 - R_m$  is the round-trip losses.<sup>9</sup> With 10% passive losses and 5% conversion losses owing to the generation of the first blue sideband, the resulting enhancement factor of  $A = 164$  strongly disagrees with the observed value of  $A = 8$  that is obtained from a fit forced through the experimental data (Fig. 5). This discrepancy cannot be explained by dispersion or by a phase shift owing to nonperfect phase matching. Both effects would detune the resonance condition for the fundamental component relative to that of the fundamental sideband. An estimation in the plane-wave limit indicates a phase shift of only 0.03 rad, which reduces the enhancement factor by only 10%.

In summary, we have demonstrated that one can significantly enhance the efficiency of cw frequency conversion by splitting the fundamental light into two frequency components. The strength of the resulting sidebands in the blue and the IR spectra deviate from the expected values for reasons yet to be identified.

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