Generating green to red light with semiconductor lasers

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Abstract: Diode lasers enable one to continuously cover the 730 to 1100 nm range as well as the 370 to 550 nm range by frequency doubling, but a large part of the electro-magnetic spectrum spanning from green to red remains accessible only through expensive and unpractical optically pumped dye lasers. Here we devise a method to multiply the frequency of optical waves by a factor 3/2 with a conversion that is phase-coherent and highly efficient. Together with harmonic generation, it will enable one to cover the visible spectrum with semiconductor lasers, opening new avenues in important fields such as laser spectroscopy and optical metrology.

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14. The reflectivity at 1006.5 nm and 2013 nm is higher than 99.98 %, while the transmission at 671 nm is 90 %. The concave mirrors have a 100 mm radius of curvature, their distance is 130 mm, and the two nonlinear crystal are aligned along this arm close to the smaller waist of the cavity. The path between the two concave mirrors passing through the plane mirrors is 400 mm long.

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18. The lambdameter is a Coherent WaveMaster^{TM} with 0.005 nm accuracy and 0.001 nm resolution. The Fabry-Perot spectrometer has a confocal geometry with 1.5 GHz free spectral range, a finesse of 200 at 671 nm and it is not sensitive to 1 μm radiation.
19. The asymetric intensity of the two frequency modes is due to the unbalanced conversion in the frequency summing crystal.
20. In a confocal resonator the familiar formula for the mode spacing (the free spectral range, FSR$= c/4L$ with c the speed of light, and L the length of the cavity) results from the spacing of $c/2L$ among both the even and the odd transverse modes, and a relative dispacement of $c/4L$ between the two classes. See also A. E. Siegman, Lasers (University Science Books, Mill Valley, California, 1986), pp. 763.
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1. Introduction

Nonlinear optics is commonly used to extend the spectrum covered by lasers over unaccessible regions [1]. For instance, second harmonic generation now is a well established process applied in frequency conversion, and with continuous wave diode lasers typically it is implemented inside resonant enhancement optical cavities [2]. Third- and up to fifth-harmonic generation is now obtained with pulsed lasers easily accessing the UV spectral region with familiar infrared diode-pumped solid-state lasers. The production of sub-harmonics, on the other hand, has important applications in metrology and quantum optics. Division in 3:1 ratio is achieved with active phase stabilization [3] and, more recently, dynamical signatures of self-phase-locking for the same process were observed [4]. Concerning the 2:1 ratio, both passive and active methods for the phase stabilization were applied [5, 6, 7]. More generally, frequency downconversion with OPO's offers a rather flexible way to access wide regions of the infrared and near-infrared spectrum, but to generate continuous-wave and single-frequency radiation one employs single resonant OPO's, which require multi Watts pump lasers [8], or double resonant OPO's which, with a modest electronic stabilization of the composing elements, show a considerably reduced threshold [5, 9].

We report on the first demonstration of optical frequency multiplication by a factor 3/2. We show that our frequency multiplier, based on a multi-resonant OPO, is inherently phase coherent, preserving the single longitudinal character of the incident field without active phase stabilization, efficient, with a 30 % slope efficiency and few tens of milliWatts threshold, and stable on time scales of the order of several minutes.

2. The 3/2 frequency multiplier

The converter is based on an OPO where the pump, the signal, and the idler fields are all resonant in the cavity and which is operated at frequency degeneracy making the signal and idler frequencies to coincide. The OPO generated field has then half the frequency of the pump, and by inserting in the cavity a nonlinear crystal for summing the pump and the OPO fields, we are able to generate radiation at 3/2 the pump frequency. Exact degeneracy operation is
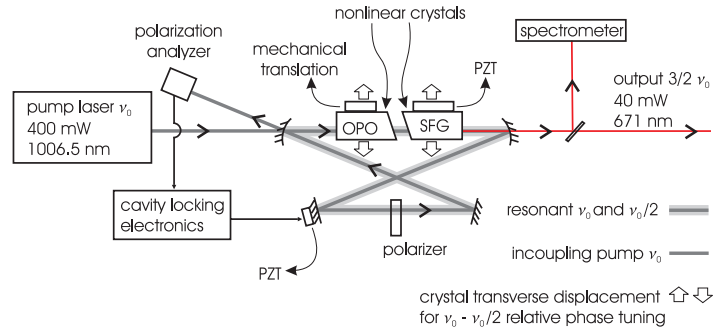
polarization analyzer

nonlinear crystals

spectrometer

mechanical translation

PZT

pump laser ν_0
400 mW
1006.5 nm

OPO SFG

output 3/2 ν_0
40 mW
671 nm

cavity locking electronics

resonant ν_0 and $\nu_0/2$

incoupling pump ν_0

polarizer

PZT

crystal transverse displacement ⇧⇩
for ν_0 - $\nu_0/2$ relative phase tuning

Fig. 1. 3/2 frequency multiplier experimental setup. A continuous wave and single fre-
quency pump laser delivering 400 mW of 1006.5 nm is converted into 40 mW radiation at
671 nm. The pump laser is resonantly coupled into a cavity where 20 mm long periodically
poled KTP [17] nonlinear crystals are set so to satisfy quasi phase-matching for degenerate
frequency down-conversion (OPO), and sum frequency generation between the pump and
down-converted light at 2013 nm (SFG). The wedged surfaces of the crystals are cut at
an angle of 100 mrad with respect to the crystal axis. The input (output) facet of the OPO
(SFG) crystal is at normal incidence. The two inclined surfaces facing each other are paral-
lel. The transverse displacement of the nonlinear crystals provides an independent control
over the cavity dispersion, insuring simultaneous resonance of the two infrared fields.

obtained owing to the double gain of the indistinguishable splitting process with respect to all
the other processes originating signal and idler photons [5].

The triple resonance condition has the advantage of reducing the threshold of oscillation on
the pump intensity down to the milliWatts level [10] and allows active stabilization of the cavity
length with respect to the pump frequency. On the other hand, the dispersive behavior of the
optical elements of the cavity, i.e. mirrors and nonlinear crystals, prevents one from controlling
the frequencies of the OPO generated fields independently, which has so far made single mode
operation in triply resonant OPO's hard to achieve. In our system the triply resonant condition
allows to actively stabilize the cavity length against the pumping laser, strongly relaxing the
requirements on the passive stabilization. We observed an oscillation threshold as low as 40
mW. By introducing an independent control on the OPO frequency modes via a fine tuning of
the relative phase accumulated between the pump and OPO-generated fields over one cavity
roundtrip we achieve the simultaneous resonance of the pump and OPO fields at frequency
degeneracy.

We demonstrate the 3/2 frequency multiplier producing radiation at 671 nm starting from a
laser source at 1006.5 nm, as schematically reported in Fig. 1. The pump laser is composed by a
semiconductor Master-Oscillator Power-Amplifier system. The master laser is an antireflection
coated diode laser stabilized on an extended cavity in the Littrow configuration [11, 12] deliver-
ing 30 mW at 1006.5 nm on a single longitudinal mode with less than 500 kHz linewidth. This
laser is then amplified to 400 mW preserving its spectral properties through a semiconductor
tapered amplifier [13]. The pump radiation is coupled into an optical cavity composed by highly
reflective mirrors at 1006.5 nm and 2013 nm, and highly transmitting at 671 nm [14]. The input
mirror has a 10 % transmission at 1006.5 nm in order to maximize the coupling of the pump
field into the cavity under resonance. One of the folding mirrors is mounted on a piezoelectric
transducer (PZT) to actively stabilize the cavity length to the pump field resonance. To this
purpose the error signal is provided by the polarization analysis of the reflected pump [15], and
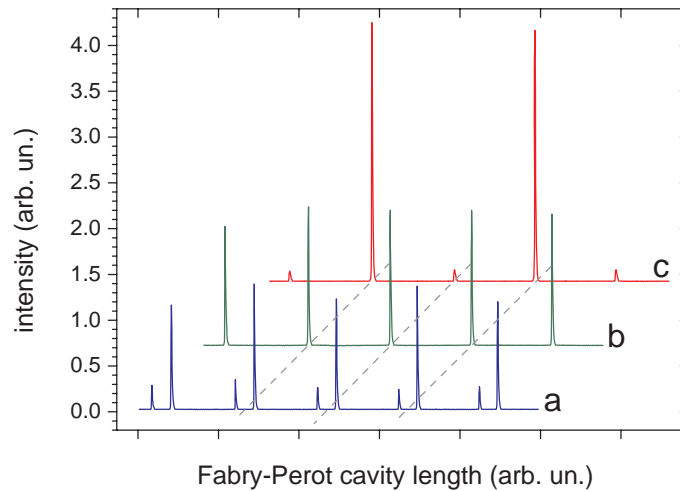by inserting into the cavity a vertical polarizer.

Fig. 2. Transmission spectra of the frequency multiplied light through a confocal Fabry-Perot (FP) spectrum analyzer. Displacing the nonlinear crystals transversally we tune the cavity dispersion in order to impose single frequency emission (b), or multi mode emission (a). c) The Gaussian beam profile of the 3/2 frequency multiplied output is verified by coupling the single frequency radiation mainly into the fundamental transverse mode of the FP cavity, which results in doubling the spacing among the resonance peaks [20].

The independent control on the OPO cavity frequency modes under pump resonance conditions is obtained by cutting the crystals with a wedged shape [16] (see Fig. 1). Displacing the crystals along the direction of the wedge enables one to change the optical path in the crystal and, due to the dispersion, it allows a fine tuning of the OPO resonance modes while keeping the cavity resonant with the pump field. The two nonlinear crystals are 20 mm long, 2×1 mm^2 cross section, periodically poled KTP [17] that insure quasi-phase-matching for linearly and identically polarized fields. The OPO and SFG crystals have a poling period of $\Lambda_{OPO} = 38$ and $\Lambda_{SFG} = 19.5$ μm respectively, and they are identically cut in an asymmetric way such that one surface is at normal incidence, while the other has an angle ϕ of 100 mrad with respect to the crystal axis. In the resonator the crystals have the wedged side facing and parallel such that the optical axis coincide. This configuration, while it allows to control the relative phase between the pump and OPO fields, it insures a negligible deviation of the beam propagation at different wavelengths, and hence simultaneous resonance of the pump and degenerate OPO fields. To reach the double resonance and frequency degenerate condition, we observe a 400 μm periodicity on the crystal transverse position. This is consistent with the calculated periodicity $\Lambda_{OPO}/\phi = 380$ μm. The crystal surfaces are all anti-reflection coated such that the reflectivity per surface is 0.1% at 1006.5 nm and 2013 nm, and 0.3% at 671 nm.

3. Spectral properties and conversion efficiency

The spectral properties of the generated red light are analyzed both with a lambda-meter for the rough wavelength determination, and a confocal Fabry-Perot spectrometer (FP) to check the

single longitudinal mode operation [18]. As expected, the spectrum of the generated red light depends on cavity dispersion. When we change the transverse position of the crystal by tens of microns we are able to switch between single frequency emission at the expected value and multi frequency emission with central wavelength displaced as much as 0.08 nm from 671 nm, with a simultaneous reduction in the output power. Figure 2 reports the typical spectra from the Fabry-Perot analyzer when the OPO operates close to the degenerate point. Depending on the transverse position of the crystals, the system emits single (spectrum 2b) or multi (2a) longitudinal mode radiation with a stability of the order of minutes. In the multi-longitudinal mode operation, energy conservation results in the symmetric positioning of the frequency components with respect to the degenerate mode [19]. The spatial mode of the red light has a nearly Gaussian profile. As a check we carefully aligned the FP analyzer in order to discern the even and odds transverse modes of the cavity [20]. As reported in Fig. 2c, we can couple 97 % of the power into the even transverse modes, indicating that at least 94 % of the generated power is in the fundamental transverse mode. While multi-longitudinal mode operation is stable on hours, when the converter emits single frequency radiation it proves to be stable on timescale of order of several minutes. Such a stability requires no active stabilization of the crystals position. Figure 3 depicts the amplitude of the generated red light when the frequency multiplier works in single longitudinal mode. The measured amplitude noise is 1.4 % RMS on a 50 kHz bandwidth.

The single longitudinal mode emission proves that the OPO works at frequency degeneracy, and it is known that for type-I phase matching (as provided by the periodically poled crystals) in frequency degenerate OPO's the pump and downconverted fields are phase locked and that they may exhibit π phase jumps [5]. On the other hand the phase of the fundamental field in the cavity is locked to that of the incident beam because of the pump-cavity resonance condition. Since the frequency sum process should not add any relevant phase noise, we have an evidence that the 3/2 multiplication process is phase coherent. A comparison with independently generated phase coherent fields will allow a thorough characterization of the stability of the phase transfer [21].

We determine the conversion efficiency by varying the pump power and measuring the generated power in the red as a function of the IR power coupled into the cavity [22]. We observe a threshold for OPO oscillation smaller than 50 mW and obtain a 30 % incremental efficiency above 150 mW pump power coupled into the cavity (see Fig. 4). Reducing the intensity of the pump below 2/3 of the full power raises the amplitude noise in the output, and makes the system more critical to operate on a single longitudinal mode. Such a degrading can be overcome by using a different geometry optimized for lower pump levels, with better focussing of the cavity mode on the nonlinear crystals, and choosing different crystals with higher nonlinear polarizability [10].

The wavelength tunability of the source can be limited either by the tunability of the fundamental laser, or by that of the 3/2 frequency multiplier. Typically anti-reflection coated infrared semiconductor lasers have a tunability of few percent in wavelength, and in our case the laser can emit from 990 nm to 1040 nm. Concerning the multiplier, the nonlinear crystals can be temperature tuned to satisfy quasi-phase-matching at different wavelengths. With our crystals, to generate radiation at 670 nm, one nm shorter wavelength, we have to tune master laser to 1005 nm, cool the OPO crystal by 5 Celsius, and cool the SFG crystal by 20. With a given choice of grating periods, a reasonable temperature tunability of the multiplier is 0.5 % in wavelength. This can be extended, without loss of efficiency, to the full 5 % tunability of the pump by using multichannel periodically poled crystals [23], which include the 10 grating periods necessary to access the relevant wavelength intervals. The mirrors of the cavity have a flat response beyond the window accessible through the master laser.
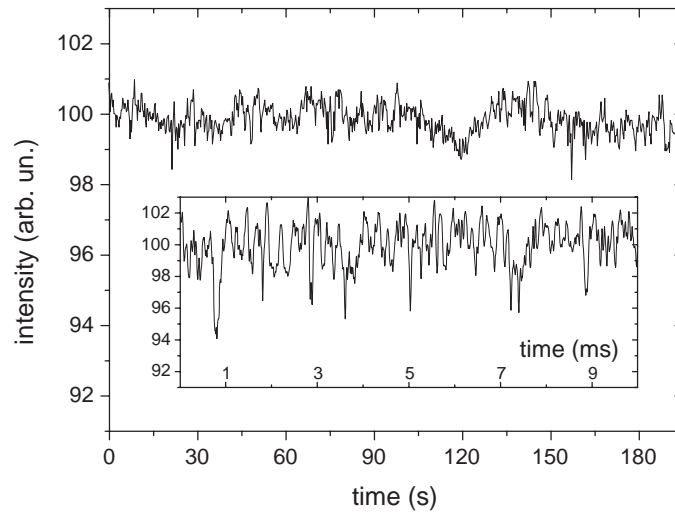
Fig. 3. Frequency multiplier amplitude stability on 3 minutes and 10 ms (inset) time timescale under single longitudinal mode emission. The measured RMS amplitude noise at full power is 1.4 % on 50 kHz bandwidth. Under multi longitudinal mode operation the amplitude stability does not not change qualitatively when measuring on the same bandwidth.

4. Conclusion

To summarize, we demonstrated for the first time a scheme to multiply the frequency of continuous wave optical radiation by a factor 3/2 and preserving its single frequency character. The frequency multiplier is phase coherent, has a high conversion efficiency, is very stable, and its stability on hours timescale could easily be achieved by optimizing the design of the opto-mechanical apparatus. Employing existing technology, the scheme will easily find applications in many disciplines requiring laser in the green to red spectral interval, such a spectroscopy. Together with integer harmonic generation, 3/2 frequency multiplication will allow to access the complete visible spectrum via harmonic generation of semiconductor lasers. It makes possible to establish phase coherent links among spectral regions distant 2/3 of an octave [24], and it may considerably simplify the realization of RGB laser systems.

It is worth noting that the frequency multiplier also acts as a parity discriminator on the pump resonant mode. In fact, neglecting cavity dispersion, the frequency degenerate and resonant down conversion can take place only when the pump is resonant in the cavity with an even number of modes. This is confirmed by the single frequency emission of the converter with a twofold periodicity when stepping the cavity length between adjacent pump resonances.
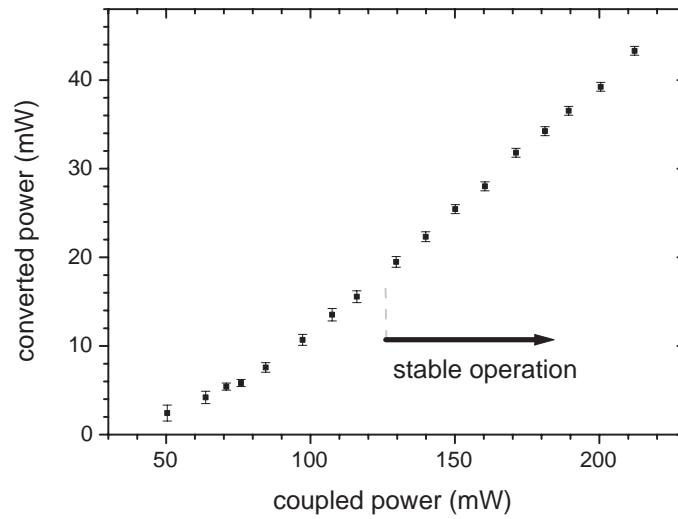
Acknowledgment

Fig. 4. Extracted power at 671 nm as function of the pump power coupled into the cavity. The vertical gray line indicates the threshold value for a stable single frequency operation of the converter. The error bars correspond to the RMS amplitude noise.