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Widely tunable sum-frequency generation in PPLN waveguide pumped by a multi-wavelength Yb-doped fiber laser

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ABSTRACT

We present some experimental results on tunable sum-frequency generation in a periodically poled lithium-niobate waveguide using a multi-wavelength fiber laser pump stabilized by a nonlinear optical loop mirror. We are able to up-convert to about 629 nm a continuous-wave infrared signal varying from 1497 nm to 1525 nm. Such a wideband conversion efficiency is ensured by the multiple spectral components of the laser pump, which is controlled by an adjustable Fabry–Perot filter. Potential applications, in particular for stellar imaging, are discussed.

1. Introduction

Stellar imaging of the infrared (IR) spectrum can provide important information in astrophysics. Unfortunately IR-detectors, especially in the far infrared, have a bad sensitivity which makes IR astronomical imaging a really challenging task. Since the late 60s, to overcome this problem, sum-frequency generation (SFG) in non centro-symmetric nonlinear crystals has received lively interest in view of its potential for detecting far IR radiations via conversion into the visible spectral range [1,2]. The Manley–Rowe laws on photon number conservation tell us that SFG-based frequency conversion takes place in absence of additional coupling with vacuum states [3] and consequently in absence of spontaneous noise. Such property can be of great interest to up-convert the frequency modes of IR photons and indeed this principle was first exploited in Ref. [2], where weak signals received by a telescope at 10 μm were made detectable as visible photons through SFG process in a Proustite crystal and a Krypton ion laser. The up-converted signals were instead detected with relatively low noise photo-multipliers at visible wavelengths.

Employing upconversion in stellar interferometry may also benefit from recent developments in other research areas. Since several years, noiseless SFG is also hotly discussed for future applications of quantum communications, as a promising tool for detecting single photons at telecom wavelengths via upconversion and the use of highly sensitive detectors for the visible spectrum [4]. Quantum frequency conversion requires the highest possible signal-to-noise ratio since the quantum information can be easily spoiled by the presence of any noise source [5]. The ultimate limit in detecting low power infrared radiation is still at present days an open cross-disciplinary point of discussion (see for instance Ref. [5]).

The conversion efficiency of SFG is limited by the quasi phase matching among the three frequency modes of pump, signal and SFG idler, which can be obtained by a periodical modification of the crystal properties. The phase matching condition in practice limits the conversion efficiency to a thin spectral band, often known as crystal spectral acceptance: as long as the crystal length grows larger, its corresponding Bloch wavevector becomes more effective and wavelength selective in completing the phase matching. Consequently the spectral region eligible for conversion gets thinner for longer crystals [6]. An appropriate trade-off between broadband response and conversion efficiency can be obtained by a number of possible solutions, ranging from engineered periodicities of ferroelectric domains up to the cascading of SFG and dif-

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ference frequency generation. In the latter case there is an unavoidable introduction of additional noise [7–10].

Astronomical radiations can be divided in several spectral bandwidths, owing to the complex absorption response of the earth atmosphere. Each bandwidth can exceed several tens of nanometers in width. As SFG requires phase matching, this constraint in practice limits the signal conversion efficiency to the crystal spectral acceptance. The longer the crystal is, the narrower the spectral acceptance becomes. On the other hand, the efficiency at phase matching increases with the crystal length. An appropriate trade-off between broadband response and conversion efficiency has to be found. But in any case, the spectral acceptance of a nonlinear crystal for SFG is typically one or two orders of magnitude narrower than the width of the astronomic bands. Therefore, more sophisticated approaches should be explored to strengthen the SFG intensity [11].

Gurski et al. [12] discussed for the first time the importance of broadband SFG in astronomical spectroscopy. They experimentally tested different techniques to broaden the SFG conversion band by using a combination of noncritical phase matching in frequency and collinear critical phase matching in angle. Other solutions are also possible like temperature phase matching tuning of the nonlinear crystal, but this solution cannot permit the simultaneity of conversion of several spectral bins of the signal bandwidth. Another approach uses engineered ferroelectric domain pattern to obtain phase matching for cascading of SFG and difference frequency generation, with the introduction of noise.

In this work we propose for the first time a new approach to broaden the effective SFG bandwidth by applying a frequency comb as pump source. We show that the very recent availability of multi-wavelength lasers (MWL) can open new scenarios in nonlinear optics. These lasers can provide an intense frequency comb [13–21] which is often developed for telecom applications. The free-spectral range (FSR) of the MWL laser can be also tunable by using special setup of the cavity. Similar laser architectures can be transposed from telecom wavelengths down to the region of 1075 nm by replacing Erbium with Ytterbium as rare-earth doping. We demonstrate that such MWL sources may be an interesting alternative to the complex engineering of ferroelectric domains in crystals for SFG in astronomy: MWL lasers can provide tens of intense discrete wavelengths and their frequency combs are also partially adjustable.

In this work we present our experimental results of SFG in a Ti-diffused PPLN waveguide pumped by a laboratory made MWL mode-locked laser. We used a periodically poled $LiNbO_3$ (PPLN) waveguide with a constant poling period manufactured by the University of Paderborn, Germany. Most of our experimental setup has been settled in fiber, in view of future applications [22] requiring long path connections among telescopes. Nonetheless, the conversion efficiency is large enough to permit the detection of SFG signals with a common avalanche photodiode when the IR signal is tuned around 30 nm, which is nearly a hundred times larger than the crystal spectral acceptance of the 40 mm long PPLN waveguide used in our experiment.

2. Principle of operation

SFG occurs in a $\chi^{(2)}$ nonlinear crystal by mixing a signal wave (at angular frequency ω_S) with a pump wave (at ω_P) to generate photons at the sum-frequency $\omega_{SFG} = \omega_P + \omega_S$. Lithium-niobate is a crystal which enjoies strong nonlinear coefficient d_{33} and mature manufactoring technology. Phase matching can be obtained on average by using periodically poled $LiNbO_3$ (PPLN) with a specific poling period Λ. Besides of phase matching, an efficient conversion requires a strong confinement of the interacting optical fields over

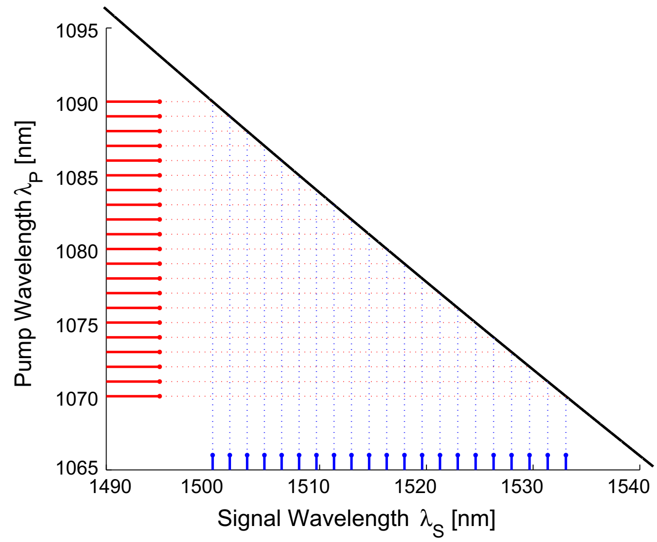

Fig. 1. Numerically calculated phase matching curve for SFG between signal (λ_S) and pump (λ_P) wavelengths.

a long interaction length. This can be obtained by using waveguides instead of bulk optics to avoid diffraction. The SFG phase mismatch $\Delta\beta$ should be then as close as possible to zero:

$$\Delta\beta = \beta_S^{TM} + \beta_P^{TM} - \beta_{SFG}^{TM} - \frac{2\pi}{\Lambda} \simeq 0, \quad (1)$$

with β_i^{TM} being the wavevector of the TM-polarized fundamental waveguide i-mode and $i = S, P,$ SFG for signal, pump and SFG wave respectively.

Our idea of broadening the upconversion spectral width a MWL pump is exemplified in Fig. 1. The black curve shows the combinations of signals and pump wavelengths giving phase-matched SFG (i.e. the condition for $\Delta\beta = 0$) for the case of a 40 mm long PPLN waveguide with a poling period of 11 μm at a temperature of 90 °C. For instance, a signal at 1524 nm can be converted by a pump at 1075 nm into the visible domain. The vertical frequency comb in red color can illustrate an ideal spectrum of a MWL laser with a FSR of 1 nm. The signal frequencies eligible for upconversion are indicated by the corresponding horizontal frequency comb in blue color. By adapting the comb lines to the spectral width of the individual phase matching curves, one would be able to cover a large spectral range for SFG-based upconversion.

3. Experimental setup

The experimental verification of our approach of broadband upconversion requires a MWL pump source. In our experiments this kind of source is based on a Yb-doped fiber laser with nonlinear feedback control. Broadband emission is possible by suppressing the mode competition due to the homogeneous line broadening at room temperature. Several architectures have been recently proposed to prevent single frequency lasing always for Erbium doped fiber lasers. One way to control the competition of lasing modes consists of modifying the cavity length with a frequency shifter like an acousto-optic modulator [13]. A similar effect can be obtained with a sinusoidal phase modulation [17]. An alternative way is to apply a nonlinear optical loop mirror (NOLM) [19,20]. NOLM are often employed as feedback control systems in optics, since they can provide a power dependent and spectrally broad transfer function. At low optical intensities the NOLM may have high transparency, which may eventually grow larger with the optical power. However the power is limited by the action of the same loop mirror which can also act as a negative feedback element whenever the power exceeds an upper threshold value. To carve the frequency comb we put a tunable Fabry–Perot filter within the laser cavity. The filter has a twofold role: its spectral transfer function controls the regular spacing of the different modes and its adjustable free-spectral-range permits us to control finely the frequency spacing of the emitted spectrum. The filter permits also to broaden the overall spectral bandwidth and then to improve the spectrum flatness. Unfortunately, by reducing the FSR we also reduce the filter finesse and hence the contrast among different modes.

In Fig. 2 we illustrate our experimental setup. The dashed rectangle identifies the MWL, while the remaining part of the scheme represents the SFG setup. The broadband optical gain around 1075 nm is provided by an Yb-doped fiber amplifier. The one-way propagation is ensured by a high-power fiber isolator. The NOLM consists of a balanced fiber coupler and a 160 m long high-birefringence (Panda type) fiber. The laser cavity evolves then in bulk optics with a system of collimating micro-lenses including a high finesse and tunable Fabry–Perot filter. The cavity is then completed by a fiber coupler: 30% of the optical power is re-injected into the cavity, while the remaining 70% is routed towards the SFG setup. We can adjust the polarization state of the light on both sides of the fiber coupler with two polarization controllers. For an appropriate choice of polarization states, and thanks to the positive feedback provided by the nonlinear phase modulation, the laser can be easily switched on with a broadband emission in a mode-locked regime. Note that the same NOLM can equally provide a negative feedback for peak powers exceeding an upper threshold level. We show in Fig. 3 the spectrum emitted by our laser source for a FSR of 1.13 nm (top) and 0.38 nm (bottom). By reducing the FSR we can increase the number of modes at the expense of the related peak contrast. In Fig. 4 we show a time domain analysis of our MWL. Such relatively long pulses can hide fast temporal fluctuations composed by closely packed sub-pulses not locked in phase among them. We cannot unveil these temporal structures, due to the limitations in bandwidth of our photodetector, but we can have an indirect signature of them from auto-correlation measurements.

The output of our MWL can be then thought as a comb of temporal modes (equally spaced by the cavity round-trip time an finely divided in subpulses) combined with a comb of frequency modes (imposed by the periodicity and finesse of the FP). This fact may in turn explain the low SFG conversion efficiencies that we obtained from our setup when using the MWL as a pump (see our discussion in Section 4). When considering a narrowband signal to convert, only one frequency mode of the MWL will satisfy the phase matching condition for being the appropriate pump. At the same time the SFG will have the temporal duty-cycle of the MWL (see Fig. 4). The duty-cycle can be even lower if we consider that only one part of the MWL pulse will have the appropriate carrier wavelength.

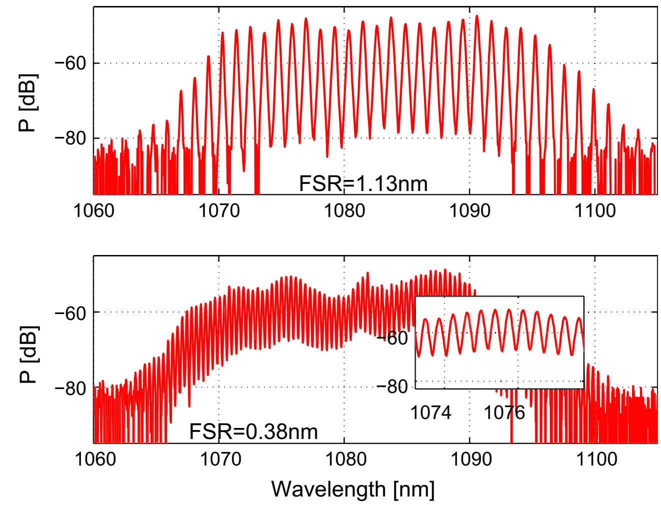

Fig. 3. MWL output spectrum for an FSR of 1.13 nm (top) and 0.38 nm (bottom). Inset: detail around 1075 nm.

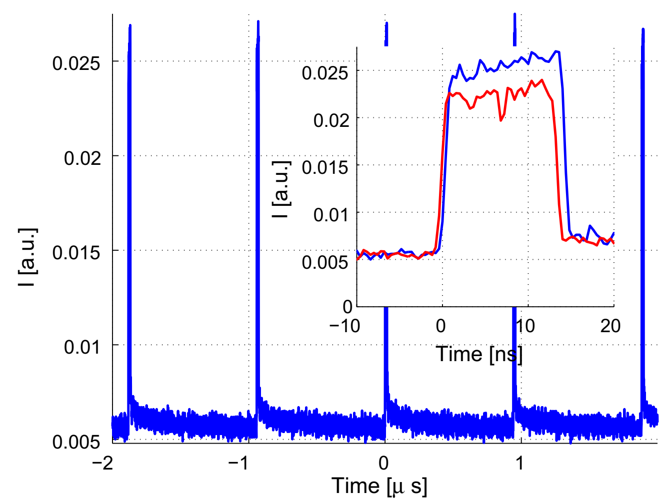

Fig. 4. Time domain analysis of the mode-locked regime. Inset: pulse duration with FSR = 1.13 nm (blue curve) and FSR = 0.38 nm (red curve). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

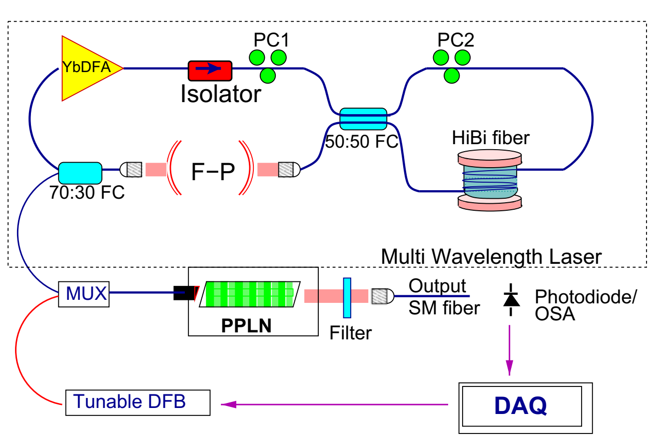

Fig. 2. Experimental setup. YbDFA, Ytterbium doped fiber amplifier; PC, polarization controller; FC, fiber coupler; F-P, Fabry Perot filter; HiBi fiber, high-birefringence fiber; DAQ, data acquisition system.

By modifying the FSR we slightly change the pulse width, while the laser repetition rate is entirely fixed by the cavity round-trip time to 1.06 MHz. The total average output power is in the order of 100 mW. The power is nearly uniformly distributed among by the different frequency modes if a large FSR (see Fig. 3, on the top) is chosen. The laser spectrum flatness is then progressively lost if the FSR is reduced. We combined the output port of the MWL with a narrow band infrared input signal from a tunable DFB laser around 1515 nm. Such a signal represents a fragment of the possible IR broadband signal to convert. For this reason we tested the SFG conversion efficiency by tuning the DFB laser wavelength over 30 nm around 1515 nm. For the experiments 40 mm long, low loss waveguides in PPLN were used providing a crystal spectral acceptance of 0.3 nm. The waveguides have been fabricated by an indiffusion of 6 μm wide, 55 nm thick Ti-stripes into z-cut $LiNbO_3$ for 8.5 h at 1060 °C. Subsequently, a periodic domain inversion by field-assisted poling with 11 μm periodicity has been performed. The end-faces are polished under an angle of 5.3° to enable coupling to an 8° slant polished fiber pigtail and to suppress multiple reflections. The PPLN waveguides are mounted in a temperature stabilized oven operated at 90 °C. Our experiments of SFG have been performed with an average pump power of about 80 mW; the DFB signal power was about 0.8 mW. The average power at 629 nm was in the range of 1 mW at the output of the single mode fiber (see SM fiber in Fig. 2). Note that in practice, besides of the SFG a competitive effect of parasitic second harmonic generation (SHG) is also present. We discriminate SFG from SHG by filtering out the latter one with a 30 nm bandwidth interferential filter around 630 nm at the output of the PPLN waveguide (see Fig. 2). The SFG radiation is coupled again into a monomode fiber at visible wavelengths prior to reach the avalanche photo-detector. This choice may seem as self defeating, owing to the large coupling losses with monomode fibers at visible wavelengths. Nonetheless, this stage is crucial for further applications in interferometry, where the visible signals must necessarily be monomode in space and in polarization state so to achieve a stable fringes contrast function.

4. Results and discussion

We illustrate in Fig. 5 the measured SFG power (in linear scale) when varying the DFB central wavelength for three different values of FSR of the laser pump. Let us emphasize that the measurements reported in Fig. 5 are not obtained by any diffractive grating or spectrum analyzer: the horizontal axis gives the emission wavelength of the DFB and the vertical axis the corresponding SFG power measured by the avalanche photodiode in the visible range. In practice the detector response is proportional to the energy integral over the whole visible spectrum. The SFG conversion progressively takes place whenever one of the MWL frequency modes is phase-matched with the signal DFB wavelength. Therefore by modifying the DFB emission wavelength between 1500 and 1530 nm and by measuring simultaneously the SFG power, we can obtain an electrical signal which follows the periodic variation of the MWL spectrum. The low SGF conversion efficiency can be explained by the fact that only a fraction of the MWL pump satisfies the phase matching for a fixes signal wavelength. At the same time the SFG idler reflects the pulsed nature of the pump whereas the input signal is in continuous wave regime.

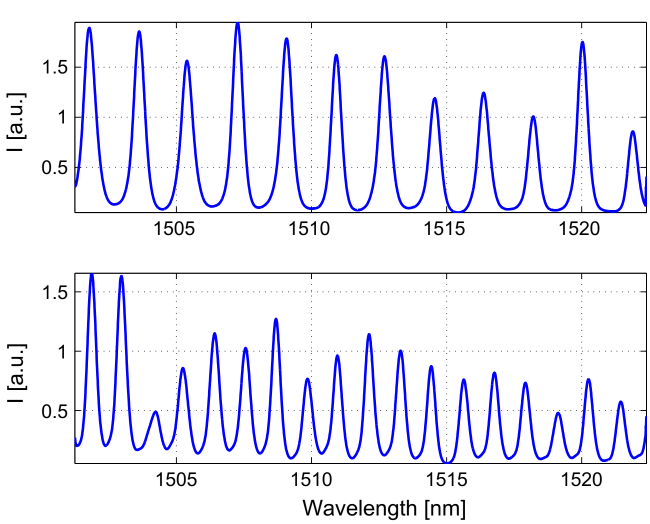

Fig. 5. Measured SFG power upon signal wavelength for various FSR of the MWL laser.

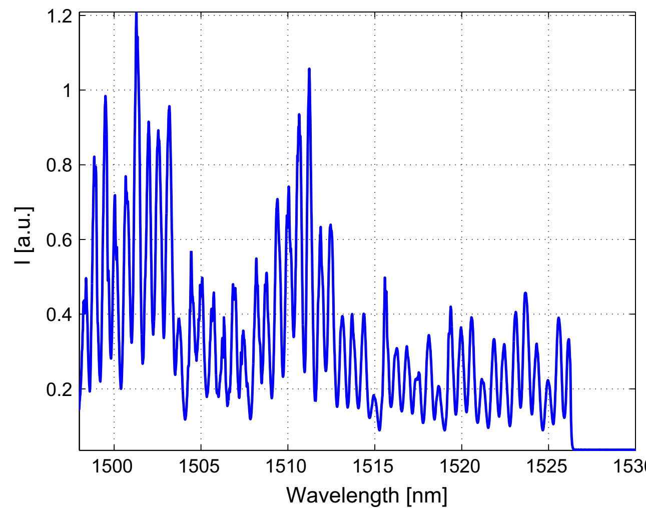

Fig. 6. Top: FSR = 1.13 nm. Left hand side, bottom: for a FSR = 0.7 nm. Right hand side: FSR = 0.38 nm.

The phase matching can be also compromised by any temperature variation of the crystal. The arbitrary units represent the voltage measured by the photodiode. More precisely we have an effect of convolution between the MWL spectrum and the crystal spectral acceptance. This result is fundamentally different from those obtainable with a narrow band pump (we tested also the narrowband pump configuration with a microchip Yag Laser at 1064 nm), where the SFG takes the form of an isolated peak around a specific signal wavelength. In Fig. 5 we show two SFG measured curves obtained with a pump having relatively large FSR of 1.13 nm (top) and 0.7 nm (bottom), respectively. The spacing between two consecutive peaks is of 1.82 and 1.15 nm in perfect agreement with our numerical simulations (see Fig. 1). We constantly monitored the stability of the DFB power: by consequence the differences in peak power are due to the non-uniform distribution of the spectral power in the MWL modes. In Fig. 6 we also show a third measured result obtained with a tight FSR of 0.38 nm. For wavelengths longer than 1527 nm one can also appreciate the zero detection level of the avalanche photodiode. Indeed that region is not covered by our MWL laser whose power spectrum edge is limited around 1075 nm (see Fig. 3 and Fig. 1 for the corresponding phase-matched SFG).

The MWL gain flatness is influenced by the FP filter spacing: this fact become evident by comparing the three cases of Figs. 5 and 6. With a FSR of 0.38 nm we are able to up-convert the DFB laser over more than 30 nm, which is a hundred times larger than the crystal spectral acceptance for a laser pump of single wavelength. Note also that the SFG power level does not return exactly to the zero detection level between two consecutive peaks when the FSR is comparable with the crystal spectral acceptance. This last fact could also be due to a poor contrast of the MWL frequency comb, which is evident only for small values of the FSR.

5. Conclusion

In this work we used a multi-wavelength laser source to obtain a widely tunable sum-frequency generation in a conventional 40 mm long Ti-indiffused PPLN waveguide. By using a pump with frequency comb we are able to up-convert to about 629 nm an infrared signal whose carrier wavelength can be freely tuned in a range of 30 nm around 1515 nm. We expect these sources may be helpful to up-convert infrared photon modes randomly distributed within broad spectral transparency bands of the atmosphere.

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