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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

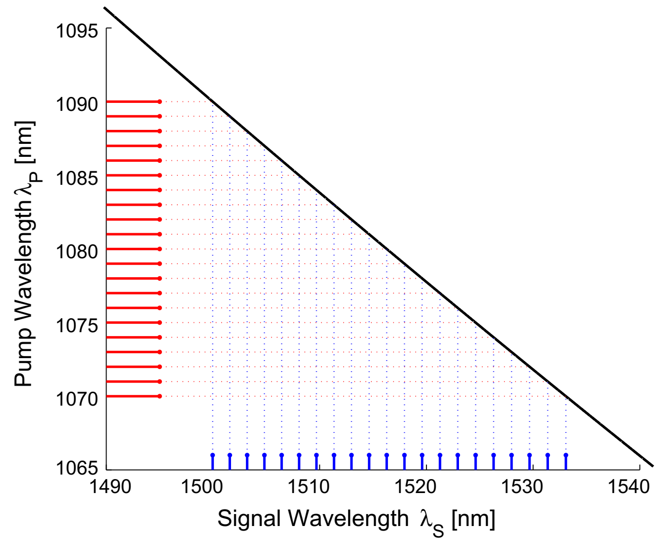

Fig. 1. Numerically calculated phase matching curve for SFG between signal (λ_S) and pump (λ_P) wavelengths.

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