Efficient generation of mid-infrared photons at 3.16 μm by coincidence frequency downconversion

This article has been downloaded from IOPscience. Please scroll down to see the full text article.

2013 Laser Phys. 23 045401


View the table of contents for this issue, or go to the journal homepage for more

Download details:
IP Address: 61.129.37.141
The article was downloaded on 06/03/2013 at 05:27

Please note that terms and conditions apply.
Efficient generation of mid-infrared photons at 3.16 μm by coincidence frequency downconversion

Kun Huang, Xiaorong Gu, Qian Zhou, Haifeng Pan, E Wu and Heping Zeng

State Key Laboratory of Precision Spectroscopy, East China Normal University, Shanghai 200062, People’s Republic of China

E-mail: ewu@phy.ecnu.edu.cn and hpzeng@phy.ecnu.edu.cn

Received 7 September 2012, in final form 8 January 2013
Accepted for publication 9 January 2013
Published 5 March 2013
Online at stacks.iop.org/LP/23/045401

Abstract
We experimentally demonstrate a pulsed mid-infrared photon source at 3.16 μm with a bandwidth of 3.7 nm by coincidence frequency downconversion with a conversion efficiency of 65%. The mid-infrared photons were generated by frequency downconversion in the saturation regime where the signal photons at 1.04 μm were synchronously pumped by intense laser pulses at 1.55 μm. In principle, the mid-infrared photon source could not only inherit the complete quantum characteristics of the input photon state, but could also be coherently manipulated in the spectral and temporal domains by engineering the classical pump field. (Some figures may appear in colour only in the online journal)

1. Introduction

Mid-infrared light has shown particular importance for applications including chemical and biomolecular sensing, infrared spectroscopy, eye-safe laser radar, and free-space communication [1–3]. Coherent radiation in the mid-infrared spectral region can be accessed normally by quantum cascade lasers [4] and optical parametric oscillators [5, 6]. Recently, nonclassical light, such as squeezed states and entangled states, have attracted increasing attention in quantum-enhanced metrology [7] and quantum information science [8], stimulating the development of mid-infrared quantum sources. Current research shows that noise-free frequency downconversion can be achievable with the preservation of all the original coherence properties [9–12]. Quantum frequency translation within the visible regime was demonstrated based on four-wave mixing via Bragg scattering in a fiber [12, 13]. However, the frequency shift is relatively small due to the low-energy phonon level transition. Compared with this, a difference frequency generation (DFG) process could provide a comparatively large frequency shift, enabling a wide-band quantum interface for visible-to-telecommunication wavelength conversion [14]. Although the sum-frequency-generation (SFG)-based upconversion detector [15, 16] and coherent quantum interface [17] were realized many years ago, their counterpart, a frequency downconverter based on DFG, was only reported recently due to the neglect of the gain saturation regime [9, 10, 14]. In principle, such a quantum frequency conversion technique could provide an efficient way to generate a mid-infrared quantum source by leveraging the mature and abundant nonclassical sources spanning from the visible to near-infrared regime.

In this paper, we experimentally present the generation of a pulsed mid-infrared source at 3.16 μm by downconversion based on DFG generation in an MgO-doped periodically poled lithium niobate (PPLN) crystal. The signal light at 1.04 μm was frequency downconverted by synchronized pump pulses at 1.55 μm with an inferred conversion efficiency of 65%. Theoretically, by feeding the frequency downconverter with a nonclassical light seed, nonclassical mid-infrared light could be generated due to the preservation of coherence properties of the signal source, which would benefit quantum metrology, quantum computation and...
quanta communication. Moreover, spectral and temporal manipulation of mid-infrared quantum states could be realized by engineering the pump pulse, which could optimize the interaction between light and matter [18]. It is also worth noting that like many SFG-based devices and experiments, the DFG-based mid-infrared source could also be facilitated compactly owing to advances in integrated optical technology [19].

2. Experimental setup

Frequency downconversion based on DFG involves a pump photon at $\omega_p$, a signal photon at $\omega_s$, and a converted photon at $\omega_c$ in a nonlinear $\chi^{(2)}$ crystal, satisfying the energy conservation relationship: $\omega_s = \omega_p + \omega_c$. Assuming a perfect phase-matching condition and non-depletion pump field, the corresponding Hamiltonian is given by

$$\hat{H} = i\hbar g E_p (\hat{a}_c^{\dagger})^2 - \text{H.c.}, \quad (1)$$

where $\hat{a}_s$ is the annihilation operator corresponding to the signal photons, $\hat{a}_c^{\dagger}$ is the creation operator corresponding to the converted photons, $E_p$ is the pump electric field, and $g$ is the nonlinear coupling constant. With an effective interaction length $L$, the dynamic of the output quantum field can be given by

$$\hat{a}_c(L) = \sin((g E_p L) \hat{a}_s(0)) + \cos((g E_p L) \hat{a}_s(0)). \quad (2)$$

As indicated in equation (2), coherent frequency downconversion can be realized as $|g E_p| L = \pi/2$ is satisfied. In such a saturation regime, the pump field at $\omega_p$ is much stronger than the signal field at $\omega_s$, thus suppressing the noise through spontaneous parametric downconversion [9].

To achieve a mid-infrared photon source by coherent frequency downconversion, we set up a synchronously pumped DFG system. The experimental setup is shown in figure 1, consisting of three parts: laser synchronization, frequency downconversion and photon detection. The laser synchronization was composed of two fiber lasers arranged in the master–slave cavity configuration. The master was a mode-locked ytterbium-doped fiber laser operating at 19.1 MHz. The output spectrum was filtered by a reflective fiber Bragg grating (FBG) to satisfy the accepting bandwidth of the MgO:PPLN crystal [20]. As a result, a 0.3 nm signal source at 1.04 $\mu$m was obtained with a pulse duration of 6 ps. The FBG transmission was then amplified by a ytterbium-doped fiber amplifier before being injected into a slave erbium-doped fiber laser (EDFL) to achieve synchronous mode-locking as shown in figure 2(a) by means of cross-phase modulation [21, 22]. A fiber band-pass filter with a 3 nm bandwidth was placed in the slave laser cavity to control the spectrum of the EDFL. The output of the EDFL was then amplified by a two-stage erbium-doped fiber amplifier. The corresponding spectrum was centered at 1.55 $\mu$m with a bandwidth of 0.5 nm. In order to improve the conversion efficiency, the pulse duration of the pump was engineered to be about 39.2 ps, which was longer than that of the signal, so that the pump pulse could be synchronously adjusted to tightly envelop the signal pulse [20, 21]. For such a passive synchronization of picosecond pulses, the timing jitter was normally about tens of fs [20], imposing a negligible influence on the temporal distribution of the signal photons within the pump pulse window. It is worth noting that in a practical quantum communication system, the single photon source and the pump laser could be separated from each other by a distance up to hundreds of kilometers. But in our experiment, the fiber link between the synchronized signal and pump sources could not extend so far due to the increasing environmental perturbations (such as acoustic vibrations, thermal fluctuations, and mechanical stresses) on the linking fiber and severe accumulated dispersion effect on the master pulses. However, the problem might be effectively solved by using an active cancellation of the fiber transmission path noise and a wide bandwidth interactivity actuator [23].

---

**Figure 1.** Experimental setup for generating a mid-infrared photon source by coincident frequency downconversion. FBG, fiber Bragg grating; Cir, circulator; Col, collimator; Atten, attenuator; L1,2, lens; DM, dichroic mirror; GP, Glan prism; PPLN, periodically poled lithium niobate crystal; FM, flipping mirror; MO, microscope objective; MF, multimode fiber; F, filter; SPCM, single photon counting module.
is the intrinsic noise only including the ambient noise and the portion introduced by the strong pump field while \( N \) is denoted as \( N \) counting rate with both (neither) signal and (nor) pump pulses blocking the signal pulses and pump pulses, respectively. The detrimental fluorescence, a long-pass filter cutting at 1 conversion efficiency on the spatial modes. To remove the variation of the coupling efficiency due to the effect of spatial modes were coupled into the fiber, thus eliminating near unity coupling efficiency was achieved to ensure all the coupling into a multimode fiber, as shown in figure 1. A from the strong pump light by a dichroic mirror before signal instead. The unconverted signal was then separated from the DFG process was difficult to detect directly, the efficiency measurement was managed by counting the unconverted measurement was monitored by the decrease of the unconverted signal photons. The downconversion process could be clearly verified by the synchronized beams of the signal and pump were anti-reflection coated at 1.04 and 1.55 \( \mu m \). The delay between the signal and pump pulses was finely tuned to get temporal overlap in the MgO:PPLN. In order to achieve a stable phase-matching condition, the nonlinear crystal was placed in a temperature-controlled oven with a temperature stability of 0.1 \( ^{\circ} C \). The operation temperature was set at 23.5 \( ^{\circ} C \) for the optimal downconversion efficiency. Because the idler beam in the mid-infrared regime yielded by the DFG process was difficult to detect directly, the efficiency measurement was managed by counting the unconverted signal instead. The unconverted signal was then separated from the strong pump light by a dichroic mirror before coupling into a multimode fiber, as shown in figure 1. A near unity coupling efficiency was achieved to ensure all the spatial modes were coupled into the fiber, thus eliminating the variation of the coupling efficiency due to the effect of conversion efficiency on the spatial modes. To remove the detrimental fluorescence, a long-pass filter cutting at 1.00 \( \mu m \) was employed before the signal beam was coupled into the fiber. Then the unconverted signal light was detected by a silicon single photon counting module (SPCM). In order to emulate the quantum light source, the signal source in the experiment was attenuated to the single photon level. In such a regime, the condition for coherent downconversion could always be satisfied due to the much stronger pump field. The downconversion process could be clearly verified by monitoring the decrease of the unconverted signal photons. We denote the counting rates of SPCM as \( N_1 \) and \( N_2 \) when blocking the signal pulses and pump pulses, respectively. The counting rate with both (neither) signal and (nor) pump pulses is denoted as \( N_3 \) (\( N_4 \)). \( N_1 \) is the background noise including the portion introduced by the strong pump field while \( N_4 \) is the intrinsic noise only including the ambient noise and dark noise of the detector. Therefore, it is easy to infer the downconversion efficiency \( \eta \) during the DFG process by

\[
\eta = 1 - (N_3 - N_1)/(N_2 - N_4). \tag{3}
\]

Since the detection efficiency of the SPCM and the transmittance of the filter system were taken into account in all the counting rates \( N_1 - 4 \), the conversion efficiency could be accurately inferred regardless of these factors.

3. Results and discussion

The cross-correlation trace could be obtained by monitoring the downconversion efficiency during the DFG process by scanning the temporal delay between the signal and pump pulses. According to the cross-correlation function, the full-width at half-maximum (FWHM) of the cross-correlation was \( \tau_c = (\tau_s^2 + \tau_p^2 + \tau_j^2)^{1/2} \) [20], where \( \tau_j \) was the timing jitter between the synchronized pulses. In our experiment, with \( \tau_s = 6 \) ps and \( \tau_p = 39.2 \) ps, \( \tau_c \) was calculated to be 39.7 ps by assuming a negligible \( \tau_j \). The cross-correlation trace in figure 2(b) showed an FWHM of 40 ps, in a good agreement with the theoretical prediction.

The downconversion efficiency as a function of the MgO:PPLN crystal working temperature is shown in the inset of figure 3. Although the low boundary of the temperature tuning curve was limited at the room temperature of 20 \( ^{\circ} C \), the temperature bandwidth (FWHM) could be clearly inferred to be 6 \( ^{\circ} C \). At the optimal working temperature of 23.5 \( ^{\circ} C \), the downconversion efficiency as a function of the pump power is illustrated in figure 3. The experimental data were fitted using a function

\[
\eta = \eta_m \sin^2(\pi P^{1/2}/2P_m^{1/2}), \tag{4}
\]

where \( \eta_m \) is the expected maximum efficiency and \( P_m \) is the corresponding pump power. By simulating the experimental data, \( \eta_m \) and \( P_m \) were estimated as 78\% and 152 mW, respectively. The peak conversion efficiency of 65\% was achieved at 80 mW, which could be further increased by enhancing the pump power, as indicated by the solid fitting line in figure 3. The downconverted mid-infrared light was then redirected by a flipping mirror into a monochromator (iHR550, HORIBA Jobin Yvon) for spectrum measurement. The spectrum was centered at 3.16 \( \mu m \) with a bandwidth of

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure2.png}
\caption{Synchronized pump and signal pulse trains (a) and cross-correlation trace (b).}
\end{figure}
3.7 nm, as shown in figure 4. Without the incident signal at 1.04 µm, the noise spectrum showed no observable peaks around the target wavelength of the DFG photons. Therefore, the detrimental fluorescence induced by the intensive pump field was remarkably reduced by using a bulk nonlinear crystal instead of waveguide as well as employing pulsed excitation rather than a continuous wave [24]. Additionally, the spectral separation between the pump and target wavelength reached 3300 cm$^{-1}$, much larger than the Stokes Raman band of MgO:PPLN (≈1000 cm$^{-1}$) [25], thus further reducing the effect of the undesirable Raman scattering noise. Since the pump pulse duration was much longer than that of the signal source, the pulse duration of mid-infrared light could be reasonably regarded to be about 6 ps. The product of the temporal and spectral bandwidth was calculated to be 0.67, which was a bit larger than the Fourier transform limit of 0.44 by assuming a Gaussian pulse shape. Therefore, the mid-infrared pulse was slightly chirped, which could be ascribed to the phase superposition by the chirped pump pulse during the nonlinear mixing process.

4. Conclusion

In summary, we demonstrated an efficient method of generating a mid-infrared source at 3.16 µm by coincidence downconversion. Near Fourier-transform-limited mid-infrared pulses were obtained with a spectrum bandwidth of 3.7 nm. The downconversion efficiency was inferred to be 65% and could be further increased by enhancing the pump power. The efficient downconversion scheme could be of critical potential for generating nonclassical mid-infrared sources by using the mature and numerous quantum light sources in the visible and near-infrared regime, such as visible [25] and near-infrared [26] single photon sources, squeezed-state light sources around 1 µm and entangled states at telecommunication wavelength [7, 8]. Additionally, the wavelength of the mid-infrared source could be widely tuned by appropriate modifications of pump wavelengths and phase-matching conditions (such as operation temperature and poling period of the nonlinear crystal) [27]. Therefore, benefiting from the wavelength tuning technique, the mid-infrared source obtained in our experiment could be applied to sensitive high-resolution spectroscopy in the fundamental absorption band of methane [28], which is promising for remote hazardous gas sensing at very low concentrations. Moreover, the output mid-infrared light could be spectrally and temporally controlled by engineering the pulse property [18, 26]. Such a nonclassical mid-infrared source generated by frequency downconversion may find promising applications in mid-infrared ultrasensitive spectroscopy by squeezed-state enhancement and free-space quantum communication with mid-infrared entangled photons [7, 8].

Acknowledgments

This work was funded in part by the National Natural Science Fund of China (10990101, 60907043, 61127014 and 91021014), International Cooperation Projects from the Ministry of Science and Technology (2010DFA04410), Key project sponsored by the National Education Ministry of China (109069), Research Fund for the Doctoral Program of Higher Education of China (20090076120024), ECNU Reward for Excellent Doctors in Academics (XRRZZ20111016), Foundation for the Author of National Excellent Doctoral Dissertation of China (PY2012004).

References


