Synchronized Fiber Lasers for Efficient Coincidence Single-Photon Frequency Upconversion

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

***Abstract*—We experimentally demonstrate a compact synchronized fiber laser system that enables fast and efficient coincidence single-photon frequency upconversion detection. Robust synchronization between the pump and signal pulses was achieved with a long-term stability. Moreover, the synchronized pulses were well-matching in both of the time and spectrum domains. As a result, a coincidence single-photon frequency upconversion was realized with a conversion efficiency of 91.8% and low background counts around 2.8×10^3 s^{-1}.**

***Index Terms*—Frequency upconversion, lasers, nonlinear optics, quantum detectors, single-photon detection.**

I. Introduction

FREQUENCY conversion is an important function for all-optical nonlinear signal processing [1]–[7]. Recently, infrared single-photon frequency upconversion detection has shown great potential for many applications [8]–[10]. By converting the infrared photons into the visible regime, silicon avalanche photodiodes (APDs) can be used to avoid the disadvantages of InGaAs APDs, such as low quantum efficiency and high dark count rate [11]–[18]. This technique typically requires a sufficiently strong pump to achieve unitary nonlinear frequency conversion in a quadratic nonlinear crystal [14]. The requisite strong pump can be achieved by using an external cavity or intracavity enhancement [15], [16] or a waveguide confinement [17], [18]. Nevertheless, a strong pump field inevitably brings about severe background noise because of parasitic nonlinear interactions. A pulsed laser with appropriate pulse duration and intensity should be better employed to convert the signal photons within a coincidence gate [19]–[21]. Due to the pulsed radiation, the background noise induced by the strong pump field can be effectively reduced. For achieving the optimum coincidence gate, specific control of the synchronized pulse durations should be concerned. This kind of technique could be benefited from recent advance in dispersion management of ultrashort fiber lasers [22]–[25].

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Near-unitary conversion efficiency of infrared single photon can be usually realized in a periodically poled lithium niobate (PPLN) crystal that provides a relatively large effective nonlinear coefficient [15], [26]. The quasi-phase-matching (QPM) bandwidth of PPLN is quite narrow ($\sim$0.3 nm) due to the limit of momentum conversation among interacting light waves. Nevertheless, typical passive mode-locked fiber lasers are operated with relatively broader bandwidth of a few nanometers. In order to realize a highly efficient single-photon frequency upconversion, it also requires optimal control of the synchronized pulses in the spectrum domain to satisfy the requisite QPM.

In our previous study, we had realized synchronous single-photon upconversion detection within a coincidence gate that showed a conversion efficiency of 31.2% [19]. However, the conversion efficiency was largely limited by the mismatch of the duration between the pump and signal pulses. Additionally, the absence of the spectral control of the pump laser resulted in lowering the energy utilization efficiency and increasing the background counts.

In this paper, we demonstrate a compact synchronized fiber laser system for highly efficient single-photon frequency upconversion detection. Due to the intracavity dispersion management and fiber Bragg grating (FBG) engineering, the effective temporal and spectral control of the fiber laser system was realized, and thus, remarkably increased the conversion efficiency. With a careful fiber laser design, the synchronized pump pulses and signal photons were well-matched in time and spectrum domains. The system showed a timing jitter of 45 fs and a long-term stability of several hours. Such a synchronization pumping scheme enabled a coincidence single-photon upconversion efficiency of 91.8% with the corresponding background counts of about 2.8×10^3 s^{-1}.

II. Experimental Setup

As shown in Fig. 1, the whole system was composed of two parts: a passive master-slave synchronization fiber laser system and a single-photon frequency upconversion counting system. Both two fiber lasers were passively mode-locked, operating at the repetition rate of 17.6 MHz to satisfy the high-speed detection. The master laser consisted of a fiber ring cavity with 1.5-m Er-doped fiber, standard single-mode fiber, and dispersion-shifted fiber. Dispersion management was achieved by designing the suitable lengths of the single-mode and dispersion-shifted fibers while maintaining the total cavity length. The output laser spectrum was centered at 1563.8 nm with a 6.2-nm full-width of half-maximum (FWHM) bandwidth [see Fig. 2(a)]. An FBG was used to spectrally filter the master laser output for approaching the QPM bandwidth of the PPLN. As shown in Fig. 2(b),

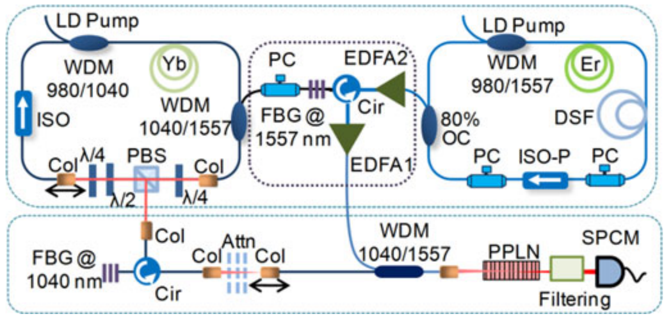

Fig. 1. Experimental setup of the synchronization pumping system. LD: laser diode; Cir: circulator; Col: collimator; PC: polarization controller; DSF: dispersion-shifted fiber; OC: output coupler; ISO: optical isolator; ISO-P: polarization-dependent isolator; PBS: polarization beam splitter; Attn: attenuator; and SPCM: single-photon counting module.

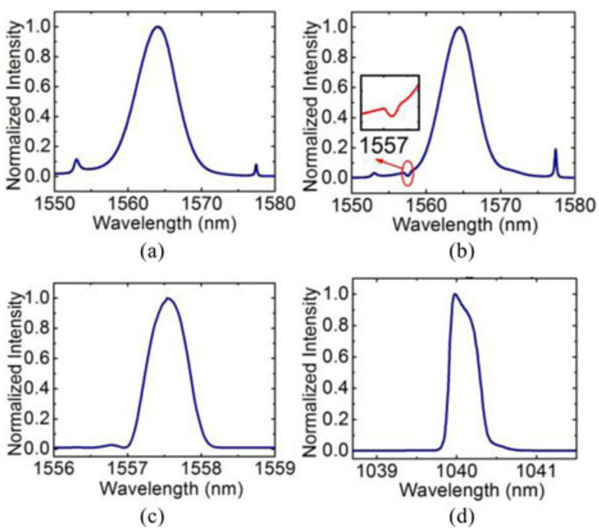

Fig. 2. (a) Er-doped fiber laser spectrum. (b) Spectrum of the FBG transmission. Inset: zoomed spectrum around 1557 nm. (c) Spectrum of the FBG reflection. (d) Spectrum of the signal source from the Yb-doped fiber laser.

a narrow spectral portion of the master laser was filtered out by the FBG reflection. The FBG reflection was further amplified by an Er-doped fiber amplifier EDFA1 as the pump source. The maximum output power reached to about 60 mW and the corresponding spectrum was centered at 1557.6 nm with an FWHM bandwidth of 0.56 nm [see Fig. 2(c)]. The FBG transmission was sent as the injection seed into the slave laser cavity through a 1040-/1557-nm wavelength division multiplexer (WDM). The transmitted frequency components were used to trigger mode locking of a Yb-doped fiber laser. Likewise, another FBG was used at the slave laser output to get spectral matching of the signal pulse. The filtered spectrum was centered at 1040.0 nm with the FWHM bandwidth about 0.35 nm [see Fig. 2(d)]. As the FBG transmission exhibited exactly the same spectral mode separation with the FBG reflection, injection locking of the slave laser could thus ensure synchronization between the FBG reflections of the master and slave laser pulses.

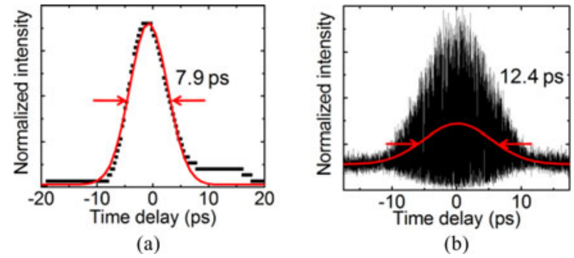

Fig. 3. Autocorrelation pulse profiles of (a) the signal source and (b) the pump source, respectively. Solid symbols in black are the experimental data and solid curves in red are the Gaussian fits to the data.

Passive synchronization was achieved by the cross-phase modulation in the slave oscillator induced by the master laser. In such master-slave configuration, the two synchronized lasers were isolated from each other, and thus, free from mutual perturbation. Compared with other passive synchronization methods such as coupled-cavity setup, the all-optical synchronization technique was simpler and more robust [27]–[31]. In the presence of self-started mode locking in the slave laser, synchronized injection locking could only be obtained within a sensitive slave cavity length match and could only last for less than half an hour at the best effort. That might be attributed to the strong competition between injection-triggered mode locking and self-started mode locking. In order to remove its detrimental influence on synchronization, we intentionally avoided self-started mode locking in the slave fiber laser by properly adjusting the laser polarization state in the cavity. This could be realized by changing the intracavity polarization state of the laser via rotating the quarter-wave and half-wave plates, respectively, placed between the fiber collimators and polarization beam splitter. In such a critical position, the mode locking would be launched only in the presence of the seed injection. By carefully adjusting one of the fiber collimators mounted on a translational stage, the cavity length of the slave laser could be changed. Eventually, the master and slave lasers were mode-locked at the same repetition rate, and the stability of synchronization was further optimized by adjusting the master laser injection polarization. The maximum cavity mismatch tolerance reached 25 μm in this system with the long-term stability of several hours.

III. Results and Discussions

The pulse duration of the signal pulse was measured by an autocorrelator with the FWHM bandwidth of 7.9 ps [see Fig. 3(a)], corresponding to the actual pulse duration of 5.6 ps by assuming a Gaussian temporal profile. In order to optimize the upconversion efficiency, the pump pulse duration relative to the signal pulse needs careful consideration [13]. The total conversion efficiency dependent on the pulse overlapping is given by

$$P_{\text{overlap}} = \int_{-\infty}^{+\infty} P_0(I_p(t)) I_s(t)\, dt \tag{1}$$

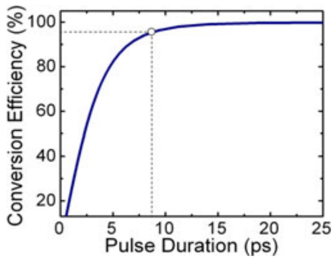

Fig. 4. Simulated conversion efficiency as a function of the pump pulse duration by assuming a Gaussian signal pulse with the FWHM of 5.6 ps. The hollow circle shows the experimental situation.

where P_0 is the probability of upconversion dependent on pump intensity I_P as sin $(I_p{}^{1/2}(t))$ and $I_s(t)$ is the normalized input pulse profile

$$\int_{-\infty}^{+\infty} I_s(t)\, dt = 1. \quad (2)$$

The simulated conversion efficiency shown in Fig. 4 indicates that the total efficiency increases as the pump pulse duration goes longer by assuming a constant FWHM duration (5.6 ps) for the signal pulse. When the pump pulse duration is much shorter than the signal pulse, the conversion efficiency is quite low, as most of the photons distribute outside of the pump pulse temporal window. On the other hand, too long pulse duration will lead to reduction of the energy utilization efficiency and increase of the background counts. Therefore, to achieve a conversion efficiency over 90% with experimentally available pump intensity, it is theoretically necessary to make the pump pulse duration somewhat longer than 7 ps.

Due to the spectral filtering by the FBGs in the experiment, the pulse durations of the master and slave lasers were stretched according to the time–frequency Fourier transforms. With the help of cavity dispersion management in the master laser cavity, the desired temporal match was achieved. Fig. 3(b) showed the autocorrelation trace of the pump pulse with the FWHM bandwidth 12.4 ps, corresponding to the actual pulse duration of 8.8 ps. In this way, the signal photons and pump pulses were well-matched temporally, guaranteeing an efficient upconversion with a relatively low background noise. According to the theoretical simulation, the conversion efficiency could reach 95.6%, as shown by the hollow circle in Fig. 4.

The timing jitter between the master and slave lasers was further measured by the cross-correlation technique. The power spectral density and the integrated timing jitter over the Fourier frequency from 1 Hz to the Nyquist frequency of 100 kHz are shown in Fig. 5(a). The timing jitter was found to be as low as 45 fs. It implied that the FBG spectral filtering produced a negligible influence on the timing jitter although the injection seed came from the FBG-filtered master laser. Such a low timing jitter would impose a negligible influence on the temporal distribution of the signal photons within the pump pulse window. So, the single-photon signal could be synchronously gated with a sufficiently high stability for coincidence upconversion detection. The cross correlation between the two synchronous pulses was also measured. The FWHM of the cross-correlation curve τ_c is related with the timing jitter τ_j by

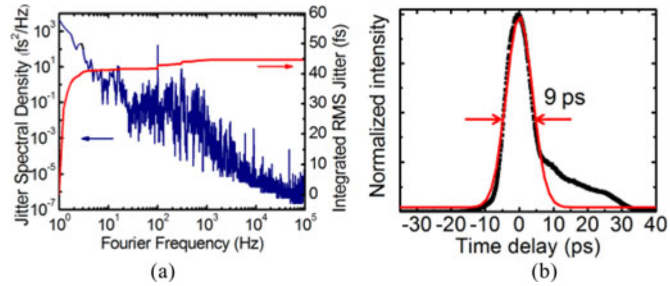

Fig. 5. (a) Timing jitter power spectral density (left) and the integrated timing jitter in Fourier domain (right). (b) Cross-correlation trace of the synchronized lasers. Solid symbols in black are the experimental data and solid curve in red is the Gaussian fit to the data.

$$\tau_c = \sqrt{\tau_s^2 + \tau_p^2 + \tau_j^2}. \quad (3)$$

With $\tau_s = 5.6$ ps, $\tau_p = 8.8$ ps, and $\tau_j = 45$ fs, we got $\tau_c = 10.4$ ps. As shown in Fig. 5(b), the measured cross-correlation FWHM was 9.0 ps, in agreement with the calculated value.

The signal at 1040.0 nm was attenuated to single-photon level about 0.34 ± 0.01 photons per pulse (5.95×10^6 s^{-1}) for the upconversion. Note that they were actually in a weak coherent state instead of a single-photon Fock state. And then, via a 1040-/1557-nm WDM, they were combined with the pump pulses into the same fiber for achieving a good spatial overlap and beam quality. The mixed beams were collimated to free space with a fiber collimator, and then, focused at the center of the precisely aligned PPLN. The two facets of the PPLN crystal were antireflection coated for the three wavelengths involved in the sum frequency generation process. For verifying the competence of the elaborately designed system, synchronously gated single-photon upconversion was performed in a 50-mm-long PPLN crystal with a grating period of 11.0 μm at the temperature of 130.4 °C, as shown in Fig. 1. Before the Si-APD single-photon counting module (SPCM), a group of spectral and spatial filters was inserted to cut down the background noise. The filtering system contained a prism, a spatial filter system, and a bandpass filter with bandwidth of 10 nm centered at 630 nm. By finely tuning the time delay for optimal temporal overlap between the signal photons and the pump pulses, the maximum photon counting of 1.86×10^6 s^{-1} was achieved at the pump power of 59.1 mW, as shown in Fig. 6. Accordingly, the maximum overall detection efficiency was 31.2%. The corresponding upconversion efficiency was inferred to be 91.8% after taking into account the transmittance of the filtering system (48.5%) and the quantum efficiency (70%) of the Si-APD SPCM. It was slightly smaller than the theoretical value (95.6%). Since the signal and pump pulses were focusing on PPLN crystal, the imperfection of the conversion efficiency might be mainly caused by the spatial mode mismatching of the pump and signal. As we chose a pump pulse of a comparatively longer wavelength than the single-photon signal in the synchronization system, the corresponding background counts were reduced down to 2.8×10^3 s^{-1} due to efficient suppression of parametric fluorescence in the PPLN crystal [12]. As a figure of merit, we calculated the noise

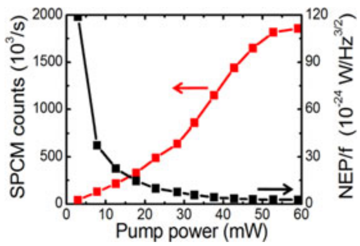

Fig. 6. Signal counts recorded by the Si-APD SPCM and NEP divided by the repetition rate as a function of the pump power.

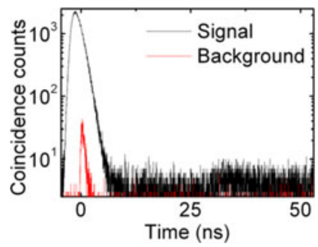

Fig. 7. Coincidence measurement between the pump pulses and SFG photons as well as the background counts.

equivalent power ($\mathrm{NEP} = h\nu\sqrt{2R_{\mathrm{BC}}}/\eta$) divided by the operation rate *f*, where $h\nu$, R_{BC}, and η are the energy of a signal photon, the background noise, and the detection efficiency, respectively. NEP/*f* was an important measure of the sensitivity of an optical detector, especially referring to the determinant of the data acquisition time in general and the key generation rate in quantum key distribution (QKD) systems [17], [19]. At the peak detection efficiency, the NEP/*f* was as low as 2.6×10^{-24} W/Hz$^{3/2}$, as shown in Fig. 6, thus showing that such scheme is suitable for the fast and efficient infrared single-photon detection.

In order to analyze the temporal distribution of the background noise in the synchronization pumping upconversion system, the upconverted photons along with the background noise were counted in coincidence with the pump pulses by using a time-correlated single-photon counting system (TCSPC, PicoHarp 300, PicoQuant). The start and stop inputs were, respectively, connected to the monitor photodiode of the pump pulse and the output of the SPCM. The coincidence counts between the pump pulses and the signal photons with 32 ps resolution and 0.1 s acquisition time are shown as the black line in Fig. 7. The fixed time delay between the inputs proved that the upconverted photons were entirely located within the pump pulse time window. The coincidence counts between the background noise and the pump pulses were measured likewise by blocking the incident signal photons. As a result of the short pump pulse duration in the synchronization system, the background counts induced by the strong pump field were effectively reduced. Therefore, the synchronous pump provided a sufficient gated coincidence for the signal photons. For continuous wave (CW) pumping scheme, the background counts were normally about 400×10^3 s^{-1} [15], [16]. Compared with CW pumping, the background counts in synchronously pulsed pumping scheme (2.8×10^3 s^{-1}) were about two orders smaller in the experiment. About 52% of the counts distributed outside of the pump pulse time window. They might arise from the scattering of background light as they were not time-correlated with the pump pulses. If the SPCM works in the gated mode, the background counts could be further reduced resulting in an improved signal-to-noise ratio.

IV. Conclusions

In conclusion, synchronized fiber lasers were demonstrated for efficient coincidence single-photon frequency upconversion. The synchronization system was robust and stable at the high operation rate of 17.6 MHz. The synchronized signal and pump laser pulses were precisely controlled; thus, desirable match in the time and spectrum domains was achieved. As a result, a maximum conversion efficiency of 91.8% was inferred with reduced background counts of 2.8×10^3 s^{-1}. Benefited from the pulsed radiation in the synchronization pumping system, high conversion efficiency was obtained with modest pump power, thus resulting in much lower background counts than that in the CW pumping scheme. Therefore, the efficient coincidence upconversion system might remarkably improve the performance of infrared single-photon detection with better signal-to-noise ratio. We believe that the compact fiber laser synchronization system for fast and efficient single-photon frequency upconversion detection is of critical potential to stimulate other promising applications, such as high-speed QKD experiments and quantum interface. The coincidence frequency upconversion system will also benefit infrared photon number resolving detector with better signal-to-noise ratio.

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