A broadband high spectral brightness fiber-based two-photon source

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Abstract: After characterizing the Raman scattering in a fused silica polarization-maintaining microstructure optical fiber, we built a fiber-based two-photon light source of high spectral brightness, broad spectral range, and very low noise background at room temperature. The resulting bright low-noise two-photon light can be used for a number of quantum information applications.

OCIS codes: (060.4370) Nonlinear optics, fibers; (190.4380) Nonlinear optics, four wave mixing; (190.5650) Raman effect.

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1. Introduction

Since the demonstration of two-photon light created by spontaneous parametric down conversion (SPDC) in a nonlinear crystal by Burnham and Weinberg in 1970 [1], thirty years of optimization have led to very bright two-photon sources [2, 3]. Using two-photon light, entangled states of up to five photons have been created [4]. SPDC converts one photon (ω_P) into two lower energy photons (ω_s and ω_i) governed by energy conservation ($\omega_P = \omega_s + \omega_i$) and phase-matching ($\vec{k}_P = \vec{k}_s + \vec{k}_i$). These constraints allow pairs of photons to be emitted into a large number of spatial and spectral modes. Unfortunately for most quantum information applications, light must be delivered in a single spatial mode and preferably with a narrow spectral bandwidth. Thus, a huge collection loss is inevitably encountered when using a SPDC source.

An ideal two-photon light source for quantum information applications would have high two-photon spectral brightness, broad spectral range, output in a single spatial mode, negligible noise background, efficient collection and delivery, and compact physical size. These requirements have led to the $\chi^{(3)}$- spontaneous four-wave mixing (SFWM) process in a single-mode fiber (SMF) receiving much attention in recent years [5-14]. At low power, SFWM is often called four-photon scattering, where two photons from the pump field (or fields) are absorbed to create a two-photon state.

Compared to free-space SPDC, a fiber-based two-photon source has many advantages. The tight confinement of the pump light into a SMF's small single transverse spatial mode results in large pump intensity (power/area) (*P/A*) and long interaction length (*L*), maximizing nonlinear optical interactions such as SFWM. The two-photon light creation, collection, wavelength selection and rejection, and wavelength division multiplexing allowed by the broad SFWM gain bandwidth, all can make use of highly evolved optical fiber technology. Having originated in a fiber, the two-photon light can be processed and delivered to a fiber communication network with minimal loss.

In a fiber-based two-photon source, the main single-photon noise background comes from Raman scattering. The amorphous nature of fused silica causes the otherwise limited Raman transition bandwidth to spread into a continuum. The Raman scattering spectrum in a fused silica SMF extends for about 40 THz ($\Delta\omega$, detuning from the pump frequency) and peaks at $\Delta\omega \approx 13$ THz. On the other hand, the SFWM spectrum is determined by fiber dispersion and Kerr-nonlinearity (n_2) according to the phase-matching condition [15],

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$$\Delta\phi = (k_{\text{signal}} + k_{\text{idler}} - 2k_{\text{P}})z + 2\gamma Pz$$
$$= \left[k^{(2)}(\Delta\omega)^2 + 2\sum_{m=1}^{\infty} \frac{k^{(2m)}}{(2m)!}(\Delta\omega)^{2m} + 2\gamma P \right], \qquad (1)$$

where $k_{\text{p, signal, idler}}$ are wave numbers of the pump, signal and idler beams in the SMF, γ is the nonlinear gain coefficient, and $k^{(2)}$ is the group velocity dispersion. SFWM is efficient for perfect (or near-perfect) phase-matching ($\Delta\phi = 0$). As the correlated signal and idler photons are detuned from the phase-matched SFWM frequencies, the phase oscillation governs energy flow between the pump and signal and idler fields as they propagate together in the SMF, determining the spectral profile of the SFWM. When group velocity dispersion is significantly less than 0, a small detuning $\Delta\omega$ is sufficient for efficient SFWM. When group velocity dispersion is close to zero, higher order dispersion terms must be included, requiring a large $\Delta\omega$ for SFWM phase-matching.

Given the Raman scattering and SFWM gain spectra, there are different approaches to design a fiber-based two-photon source. A recent experiment [14] showed that at room temperature the visibility of the two-photon light produced in a conventional SMF by SFWM with a small $\Delta\omega$ is limited by the Raman scattering. Liquid nitrogen cooling is needed to deplete the fiber phonon population to achieve a high two-photon coincidence/accidental contrast (C/A) of 100. While this method is a good demonstration of an all fiber-based two-photon source, there are a number of disadvantages. With the small detuning, rejecting scattered light from the pump requires difficult wavelength filtering. The liquid nitrogen cooling required for high two-photon visibility that is necessary for many quantum information applications adds complexity to the operation of the source. Another disadvantage is the limited bandwidth available for use [16].

In our initial experiments [11, 12], we showed the feasibility of creating a bright source of two-photon light using SFWM in a microstructure fiber [17, 18]. The key feature enabling this is the greatly reduced mode area of microstructure fibers that effectively increases the fiber nonlinearity by one order of magnitude over that of conventional SMFs. The particular air-hole pattern also allows more flexibility in designing the fiber dispersion to meet different applications, for example, to have SFWM with large frequency detuning so that the Raman scattering gain is negligible.

In this paper, we present a more detailed experimental study of two-photon light production in a fused silica polarization-maintaining microstructure fiber (PMMF). This polarization characteristic allows for better control of experimental parameters. After characterizing the Raman scattering spectrum of the PMMF, we implemented a two-photon light source with high spectral brightness and negligible noise background over a broad spectral range. With this version of the source, we measured two-photon coincidence rates at the 100 Hz level with C/A = 1000, the best known to date.

2. Experiment and discussions

In our experiment, we orient vertically the polarization of all the light pulses, the principal axis of the PMMF, and all other polarization sensitive optical elements. A linearly polarized laser pulse with λ = 740.7 nm with a repetition rate of 80 MHz is coupled into the 1.8 m PMMF[*] [19]. The light output from the PMMF is directed to an optical grating after passing a polarizing beam splitter to remove any horizontally polarized photons created, for example, by power-induced birefringence and cross $\chi^{(3)}$-interactions. We used a two-pass grating

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[*]Certain trade names and company products are mentioned in the text or identified in an illustration in order to specify adequately the experimental procedure and equipment used. In no case does such identification imply recommendation or endorsement by the National Institute of Standards and Technology, nor does it imply that the products are necessarily the best available for the purpose.

configuration to enhance the signal collection and suppress noise. The setup is similar to an optical stretcher (or compressor) commonly used in ultra-fast lasers to implement chirped-pulse-amplification. This two-pass configuration accomplishes three functions: (1) selection of frequency-correlated signal (shorter wavelength, $\Delta\lambda$ = 0.8 nm) and idler (longer wavelength, with $\Delta\lambda$ = 1 nm) photons created by SFWM, (2) double-rejection of photons at other wavelengths, and (3) preparation of the selected photons back into a single-spatial mode for high collection efficiency.

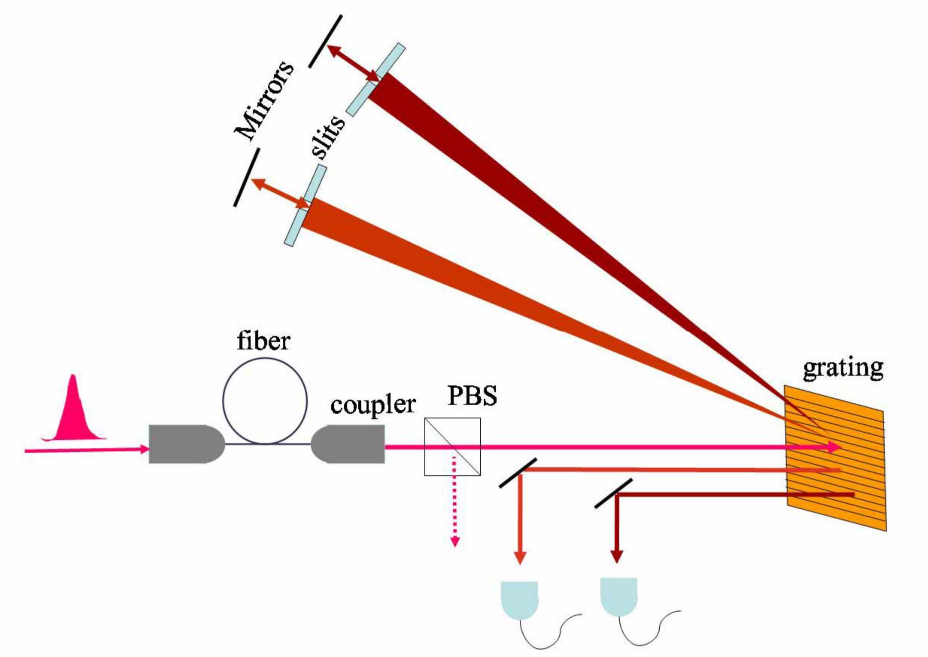

Fig. 1. Creation of two-photon light by degenerate SFWM. A two-pass grating configuration with polarizing beam splitter (PBS) is used. The signal and idler photons selected by adjustable slits are retro-reflected back to the grating, and put back into single spatial modes upon exiting the grating. They are collected into SMFs to be fed into single photon detectors.

The correlated signal and idler photon pairs selected by wavelength-matching [11, 12] are coupled into SMFs which are connected to single-photon detectors. At low power, photons created in the PMMF are due to either SFWM or Raman scattering. Figs. 2(a) and (b) show that the signal (D_{signal}) and idler (D_{idler}) photon rates have a quadratic increase with pump power, the signature of SFWM. Using these rates, and the two-photon coincidence (D_{coin}) and accidental coincidence (D_{acci}) rates, we can estimate the individual photon production rates by the SFWM or the Raman scattering processes, respectively. For example, the idler photons produced in the PMMF by the Raman scattering process can be estimated to be

$$N_{idler} = \frac{D_{\text{idler}} - D_{\text{idler-background}}}{\eta_{\text{idler}}} - \frac{D_{\text{coin}} - D_{\text{acci}}}{\eta_{\text{signal}}\eta_{\text{idler}}}, \qquad (2)$$

where η_{signal} and η_{idler} are signal and idler photon detection efficiencies, and $D_{\text{idler-background}}$ is the idler channel background noise including pump scattering, stray light, and detector dark currents.

At low power, this photon rate is proportional to the Raman scattering gain $R(\Delta\omega)$ [20-23] as

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$$N_{\text{idler}} = R(\Delta\omega) L_{\text{eff}} BP\left(1+\frac{1}{e^{h\omega/kT}-1}\right), \tag{3}$$

where L_{eff} is the effective fiber length, B is the photon collection bandwidth, and the last term accounts for the phonon distribution.

Using Eqs. (2) and (3), the Raman scattering spectrum of the fused silica PMMF was extracted(Fig. 2(c)), and found to be consistent with that of the conventional fused silica SMF [15]. The influence of the Raman scattering-produced single-photon background noise to the SFWM-produced two-photon light is evident in the measured spectrum of two-photon coincidence/accidental (C/A) contrast. The lowest C/A value was seen at the position of the Raman scattering peak. The C/A contrast increases significantly as $\Delta\omega$ moves away from the Raman scattering peak, with downward modulations by the Raman scattering (Fig. 2(e)).

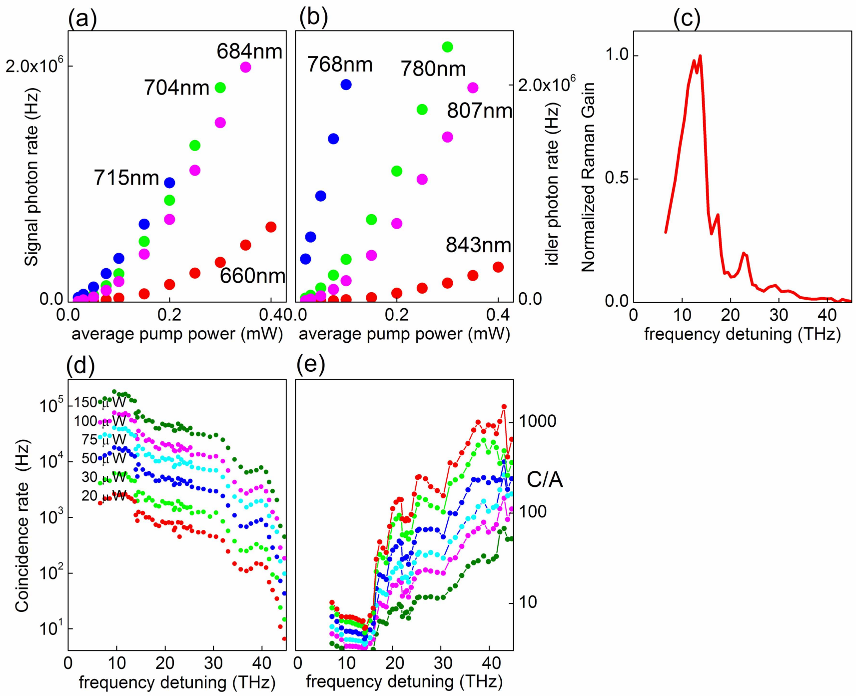

Fig. 2. Measured signal photon (a) and idler photon rates (b) at a range of wavelengths. Signal and idler wavelengths in the same color are correlated. (c) Normalized Raman scattering gain. Measured two-photon coincidence rate (d) and coincidence/accidental contrast (e), where results with same pump powers are labeled with the same color.

With these settings, between $\Delta\omega \approx 20$ THz and 30 THz, we observed high SFWM gain and C/A contrasts of over 100 (Fig. 2(e)), yielding a 10 THz 3 dB gain bandwidth for the two-photon light. With an average pump power of 30 μW, we measured a two-photon coincidence rate of 1 kHz, with C/A > 100 (in a 0.4 THz bandwidth (≈ 1 nm)). This result is significant for several reasons. First, this high two-photon coincidence rate and high C/A contrast were achieved at the same time in a fiber-based two-photon source. Second, this bright two-photon light is available over a broad spectral range, allowing for simultaneous multiple-wavelength operation that could potentially make use of wavelength-division-multiplexing at high rates and high C/A contrasts. Third, because the two-photon production rate is proportional to (BP^2), while the Raman scattering rate is proportional to (BP), it is possible to improve the two-photon coincidence rate while maintaining contrast. Finally, the experiment was carried out at room temperature.

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Our present PMMF-based two-photon source brightness is comparable to the best SPDC, which produces two-photon light at ~100 kHz/nW/mW [24-26]. In addition, with the two-photon light created in a single spatial mode, photon collection, filtering, and delivery can be accomplished with minimal loss.

At even larger detuning of $\Delta\omega \approx 40$ THz, we observed a very high C/A contrast of 1000 at a two-photon coincidence rate of 100 Hz. This relatively high rate with extremely high two-photon purity can be useful for fundamental quantum mechanics tests.

For our PMMF, the SFWM gain spectral region overlaps the region of peak Raman scattering gain, where although the two-photon coincidence rate is maximized, the C/A contrast is less than 10. This suggests that a fiber with similar gain, but bigger dispersion slope, could shift the SFWM gain peak away from the major Raman scattering gain spectral region, leading to a two-photon light source with much higher spectral brightness and low single photon noise background. We believe that such fiber engineering is practical.

In conclusion, our experimental study of a PMMF confirms that fiber-based two-photon sources can have many advantages over SPDC sources, and that SFWM with large frequency detuning is better than small detuning, for the creation of two-photon light. A fiber-based two-photon light source has high two-photon spectral brightness, a broad spectral range, output in a single-spatial mode, negligible noise background, efficient collection and delivery, and compact physical size. With appropriate dispersion management, the fiber-based two-photon source can meet a range of quantum information applications, from the ultraviolet to the infrared, for free-space and long haul communication.

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