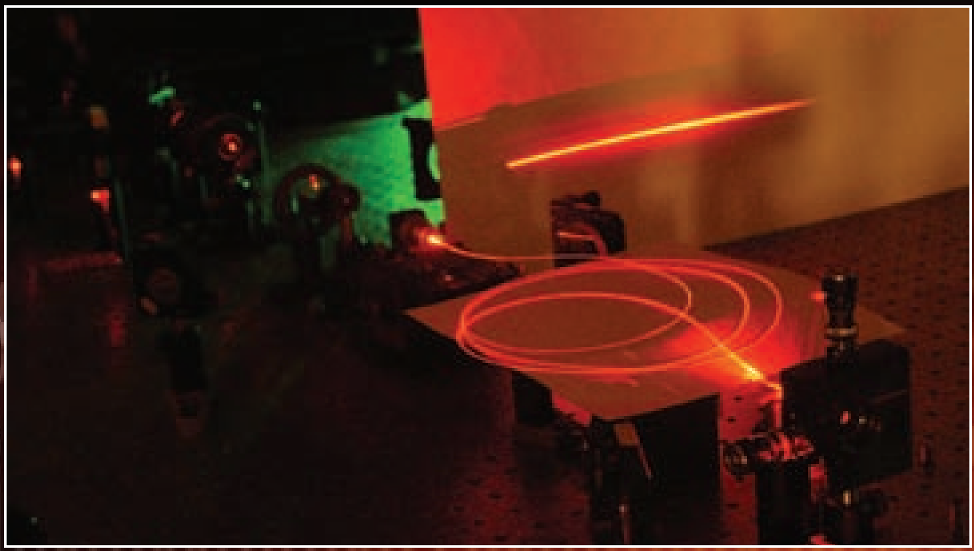

Bright broadband light generated in a highly nonlinear microstructure fiber.

Jingyun Fan, Alan Migdall and Lijun Wang

A Twin Photon Source

A new light source brings quantum cryptography closer to reality.

The art of secret communication is as old as human history itself. The two major methods for doing this are steganography, which refers to hiding a message (rarely used in modern times) and cryptography, or the hiding of the meaning of a message. Nowadays, the only absolutely secure way to encrypt a message is to shift each letter by a random amount, and to use that random "key" only once.

Thus, the most important question in cryptography today is how to distribute a random string of bits between two and only two parties—the sender and the receiver. One solution to this problem is public key cryptography (including the well-known RSA method), which relies on the difficulty of factoring a large number. However, its absolute security cannot be guaranteed.

Quantum cryptography takes another approach. Here, a single photon is the physical carrier of information, and its

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Based on Optical Fiber

quantum mechanical state is used to encode one bit of the key. While there are numerous protocols, quantum key distribution fundamentally relies on a special property of the quantum world: A single photon can be detected only once!

In other words, eavesdropping is not possible: Detecting and duplicating the single photon's quantum state—that is, sending one copy onward in a message and keeping one as a record—is simply prohibited by the laws of quantum mechanics. Even better, the integrity of the key distribution channel (whether an eavesdropper is listening) can be tested by examining the errors the channel produces, with various test quantum states as input.

An excellent way to realize the fantastic and almost fairy-tale-like applications that might spring from this form of cryptography is through reliable, high-performance single- and multi-photon entangled sources. Practical implementations of such sources are most commonly made from sources that produce photons in pairs. Therefore, researchers are working hard to build bright robust two-photon light sources that emit photon pairs that can be built into two- or more-photon entangled states.

In 1970, Burnham and Weinberg demonstrated two-photon light created by spontaneous parametric down conversion (SPDC) in a nonlinear crystal. The 30-plus years of optimization since then have led to bright two-photon sources. In SPDC, a pump photon at a high frequency ω_p is converted into two lower energy photons (called signal and idler), satisfying energy conservation $\omega_p = \omega_{signal} + \omega_{idler}$, and the phase-matching condition, $\vec{k}_p = \vec{k}_{signal} + \vec{k}_{idler}$. In a nonlinear crystal, pairs of photons are often emitted into a large number of spatial and spectral modes.

However, for communications applications, light must be delivered in just a single or a few spatial modes and preferably with a narrow spectral bandwidth. Thus, researchers inevitably encounter a large collection loss when using SPDC as the source.

An ideal two-photon light source for quantum information applications would have high two-photon spectral brightness, a broad spectral range, output in a single-spatial mode, negligible background noise, efficient collection and delivery, and compact physical size.

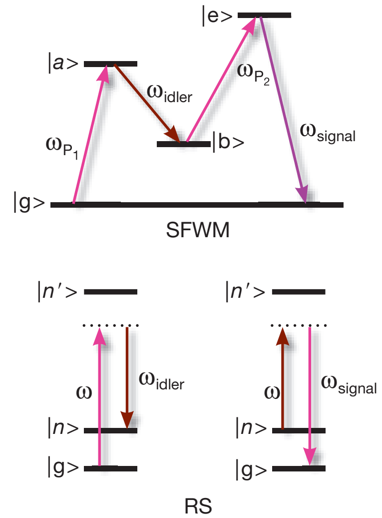
Those familiar with fiber optics will immediately think of high-gain fiber parametric amplifiers. Such amplifiers have been extensively studied at high powers for optical signal amplification in communication networks. However, the low power extreme may be ideal for two-photon generation. Here, a parametric four-photon process occurs, where two pump photons are consumed to produce two output photons.

Fiber nonlinearity

A typical single-mode optical fiber (SMF) is made of fused silica and is cylindrically symmetric. With proper core size and refractive index difference between the fiber core and cladding, light propagates in a single-spatial mode with low loss. The small effective mode area (A_{eff}) of the light beam inside the SMF (about 50 μm^2 for λ = 1.55 μm), together with a long fiber length (L), leads to a high overall nonlinear interaction that is proportional to PL/A_{eff}, where P is the input power.

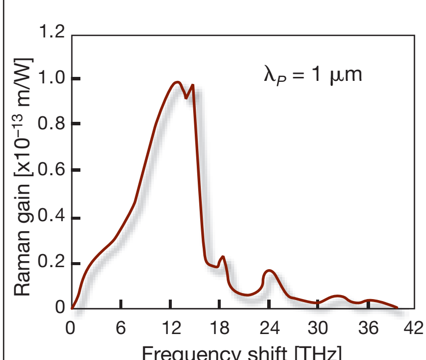
Because glass is centrosymmetric, second-order nonlinear susceptibility, $\chi^{(2)}$, is absent in SMFs. Hence, the dominant nonlinear interactions in an SMF are $\chi^{(3)}$ processes. Among third-order nonlinear processes, the most important ones for the creation of two-photon light are

Energy diagrams for SFWM and Raman scattering



In spontaneous four-wave mixing (SFWM), two photons are absorbed from the pump fields (ω_{P_1} and ω_{P_2}) to create two new photons ω_{signal} and ω_{idler} that are correlated due to energy conservation. In Raman scattering a single pump photon interacts with a phonon to produce a photon of higher/lower energy ω_{signal} /ω_{idler}.

Raman scattering gain in a typical fused silica SMF



spontaneous four-wave mixing (SFWM) and spontaneous Raman scattering (RS).

SFWM and RS typically occur together. 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. RS, on the other hand, shifts a single-pump photon to a different wavelength, resulting in the main noise background for the two-photon light created by SFWM.

In the figure on the left, we readily see the physical origin of twin photon generation. Here, two pump photons (ω_{P_1} and ω_{P_2}) are consumed to create ω_{signal} and ω_{idler}. These two new photons are created simultaneously to satisfy energy conservation. Because the two modes, signal and idler, initially have no photons in them, the newly created twin photons can be perfectly correlated.

For cryptography, the signal photon can be sent out as the carrier, while the idler is detected as a trigger to indicate that a signal photon has been generated and sent out. The Raman process is the main source of error that can destroy this perfect correlation. For example, if the Raman process only adds a signal photon without an idler, it will spoil the correlation.

The efficiency and spectrum of SFWM is mainly governed by phase-matching through fiber dispersion and Kerr-nonlinearity (n_2). The fiber dispersion is determined by both material dispersion and waveguide dispersion and leads to the propagation phase-mismatch $\Delta kz = (k_{P_1} + k_{P_2} - k_{signal} - k_{idler})z$ of the four different optical fields in the SMF, where z is the propagation distance. The Kerr-nonlinearity is the optical power-induced variation of refractive index that causes a shift of the phase-mismatch by $\gamma(P_1 + P_2)z$.

Here, γ is the nonlinear gain coefficient with $\gamma = 2\pi n_2/\lambda A_{eff}$. When these two phases cancel in an SMF, the SFWM is phase-matched, with $\Delta kz + \gamma(P_1 + P_2)z = 0$. Energy is transferred from the pump fields (ω_{P_1} and ω_{P_2}) to the initially absent signal (ω_{signal}) and idler (ω_{idler}) fields as the four fields propagate together in the fiber.

The Raman process in fused silica SMFs has been long known. Fundamentally, pump photons induce transitions in the fiber glass vibrational bands. This is frequently described as an inelastic scattering process and characterized as a phonon exchange process. The amorphous nature of fused silica spreads the otherwise limited Raman transition bandwidth into a continuum.

Among third-order nonlinear processes, the most important ones for the creation of two-photon light are spontaneous four-wave mixing (SFWM) and spontaneous Raman scattering (RS).

The RS 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. In addition, the RS process can cascade if pump power is high enough to drive secondary RS processes. At low power, the first-order RS spectrum is the single-photon noise distribution, which must be accounted for in a fiber-based two-photon light source.

Optimizing SFWM vs. RS in the fiber

The generation of correlated two-photon states via the SFWM process in a single-mode optical fiber was first proposed in 1999 (NEC Research Inst. Technical Report, TR99-106 and J. Opt. B: Quantum Semiclass. Opt. **3**, 346), and then developed by the NEC-NIST team along with others. Subsequently, a team from Northwestern University demonstrated a similar scheme using a dispersion-shifted fiber (Opt. Lett. **26**, 367). They took advantage of the anomalous dispersion spectral region, where SFWM occurs with small detuning $\Delta\omega$ and low Raman gain.

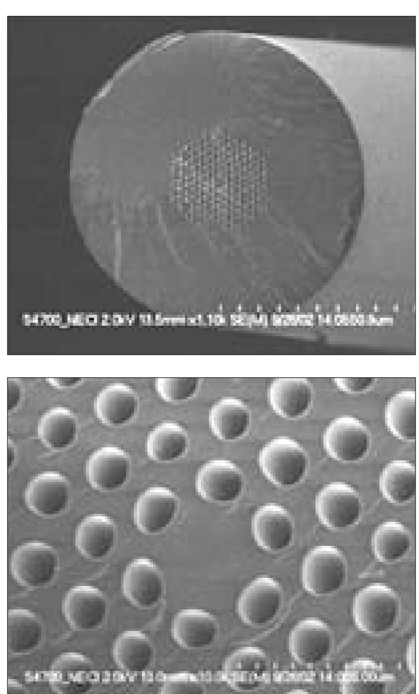
They demonstrated a two-photon correlation significantly above the noise level in a 300-m dispersion-shifted fiber (DSF). The measured two-photon coincidence/accidental contrast (C/A, effectively a signal-to-noise ratio) was about 20 at room temperature and later 100 with liquid nitrogen cooling to deplete the phonon population in the DSF. They then used their fiber source to create polarization-entangled two-photon light with a visibility of 98 percent.

While this method is a good demonstration of an all-fiber-based two-photon source, it has a number of disadvantages. When the detuning $\Delta\omega$ is small, rejecting pump light requires difficult wavelength filtering. The liquid nitrogen cooling that creates the high two-photon visibility needed for many quantum information applications adds complexity to the operation of the source. Another disadvantage is the limited bandwidth available for use.

Knowing that the Raman gain drops significantly for large detuning $\Delta\omega$, while the SFWM bandwidth is broad, we use SFWM with a large frequency shift $\Delta\omega$ to produce two-photon light with high performance.

There are two important technical facts related to SFWM in fibers that can be used to advantage. First, the gain of phase-matched SFWM at low power is proportional to $(\gamma Pz)^2 \propto (n_2 \cdot 1/A_{\mathrm{eff}} \cdot Pz)^2$. While one can increase the SFWM gain by increasing the product of Pz, this also adds unwanted multi-photon emission through stimulated FWM and RS processes. This can be avoided by reducing the effective fiber area using microstructured fibers (MF). Another advantage is that an MF's dispersive behavior can be designed to enhance the phase-matching conditions.

Scanning Electron Microscopy (SEM) image of a microstructure fiber



An MF is a one-dimensional periodic structure patterned with air-holes running parallel to the fiber's optical axis, with one of the air holes missing. The region with the missing hole serves as the fiber core with the surrounding air hole region acting as a cladding with a lower refractive index. Because the air-hole region can be engineered to be mostly holes with very little glass, the cladding index can approach one.

The large difference in refractive index between the core and the cladding allows one to make the core size very small, while allowing a very broad spectral range of wavelengths to propagate in a single spatial mode with low loss, thus creating what is referred to as spectrally endless single-mode fiber. The effective mode area of an MF is typically one order of magnitude smaller than that of conventional SMF, increasing the effective fiber nonlinearity by 10 times.

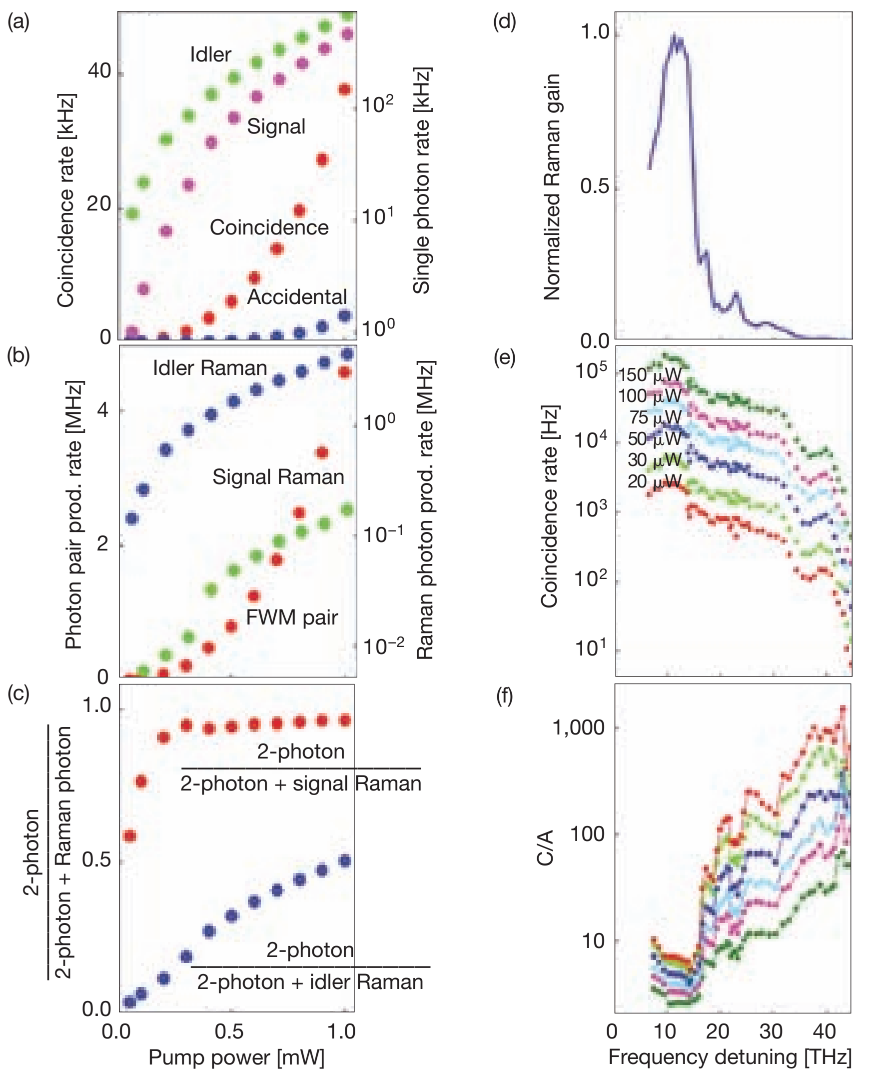
Due to this higher nonlinearity, lower pump powers are needed to achieve the same two-photon signal. In addition, it is possible to improve significantly the C/A ratio with an MF because the Raman background is simply linearly proportional to the pump power. However, with these advantages also come at least one potential problem—the increased complication of coupling light from an MF to a conventional SMF.

Making the fiber core smaller not only effectively increases the fiber nonlinearity, it also moves the zero-dispersion wavelength (λ_{ZDW}) to shorter wavelengths. This provides additional flexibility in designing fiber with appropriate dispersion properties to create two-photon light by SFWM at a range of desired wavelengths to meet different applications.

Degenerate SFWM with a large frequency detuning in an MF

The most frequently used SFWM scheme takes two photons absorbed from the same pump field (ω_p) to create a pair of signal and idler photons, $\omega_{signal} - \omega_p = \omega_p - \omega_{idler}$. When the pump wavelength is close to λ_{ZDW}, a large frequency detuning $\Delta\omega$ is needed for efficient SFWM. Appropriate dispersion management can move the SFWM gain away from the Raman peak so that the single-photon noise background is low.

Two-photon and single-photon light



We examined the two-photon and single-photon light produced in a 1.7 m MF (γ=100/W/km) with an 8 ps laser pulse at a repetition rate of 80 MHz. From the measured signal photon (D_{signal}), idler photon (D_{idler}), two-photon coincidence (D_{coin}) and accidental (D_{acc}) rates, plotted in (a), we estimated the single photon (N_{signal} and N_{idler}) and two-photon production (N_{two}) rates using detection efficiencies η_{signal} and η_{idler}. $N_{two} = (D_{coin} - D_{acc})/(\eta_{signal}\eta_{idler})$, $N_{signal} = D_{signal}/\eta_{signal} - N_{two}$, $N_{idler} = D_{idler}/\eta_{idler} - N_{two}$. They are plotted in (b). We further estimated the ratios $N_{two}/(N_{two} + N_{signal})$ and $N_{two}/(N_{two} + N_{idler})$ representing the contrast of SFWM to Raman at the collected signal and idler wavelengths; they are plotted in (c). With this photon counting method, we obtained the Raman spectrum by scanning the idler and signal wavelengths using a fused silica polarization-maintaining MF (γ = 70/W/km, λ_{ZDW} = 745 +/– 5 nm, length = 1.7 m), as shown in (d). We measured two-photon light with high spectral brightness over a broad bandwidth and high C/A, as shown in (e) and (f).

In our experiment, we optimize the overall SFWM gain and the SFWM gain with respect to the Raman gain, using a two-pass grating that enhances the signal collection and suppresses noise. The set-up is somewhat 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 and idler photons created by the SFWM process; (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.

At a big detuning of the signal and idler from the pump, we measured a high two-photon coincidence rate of 1 kHz per bandwidth of 0.44 THz over a 10 THz spectra range (from $\Delta\omega$ = 20 THz to 30 THz), with C/A > 100 with the pump wavelength close to λ_{ZDW} at an average pump power of 30 µW coupled into a polarization-maintaining MF (γ = 70 /W/km, L = 1.7 m). The 10 THz bandwidth provides an opportunity to use two-photon light along with WDM components common in telecom networks. The estimated two-photon production rate per bandwidth per mW pump power is comparable to the best SPDC-based sources (about 100 kHz/mW/THz).

The spectral brightness over a broad bandwidth in single spatial mode with very low background noise, combined with the sophisticated fiber optical technology and compatibility to global network, provides an all-fiber-based two-photon source with great potential. Operated at room temperature, SFWM with large $\Delta\omega$ also offers better spectral brightness, available bandwidth, background noise, flexibility, and stability than SFWM with small $\Delta\omega$.

Moving the pump wavelength further toward the normal dispersion region requires a large $\Delta\omega$ for efficient SFWM. One is able to design an MF with appropriate dispersion to allow pumping at 1,064 nm to create the idler photon at 1,310 nm and the signal photon at

In our experiment, we optimize the overall SFWM gain and the SFWM gain with respect to the Raman gain, using a two-pass grating that enhances the signal collection and suppresses noise.

895 nm. This adds convenience, as the signal photon can be detected with silicon avalanche photodiode with its high detection efficiency at 895 nm. Rarity and his colleagues recently demonstrated an experiment of this sort (Opt. Express **13**, 534 and 7572).

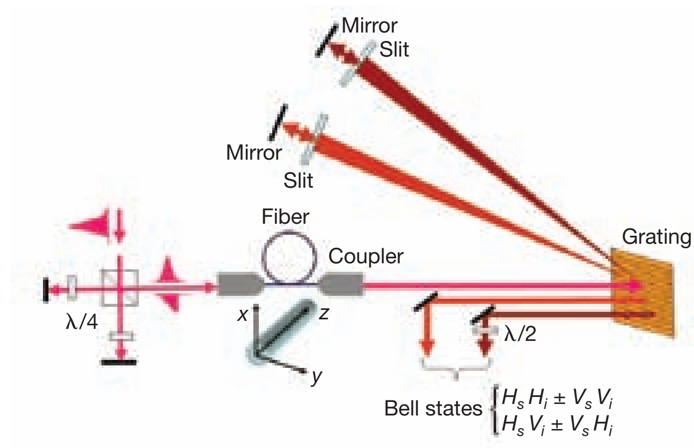
Two-photon quantum entanglement can be built from SFWM-produced two-photon light in a number of ways. In the co-propagating scheme, two cross-polarized pump beams are coupled into the fiber, each creating a correlated two-photon state along its polarization in the form of H_sH_i or V_sV_i (H and V indicate horizontal and vertical polarizations and s and i indicate signal and idler photons, respectively.)

With appropriate control of temporal coherence and polarization, these two photon pairs are indistinguishable upon exiting the fiber and so can form Bell states. The Northwestern team demonstrated such an experiment.

Counter-propagating and two-fiber schemes are also used to prepare polarization-entangled two-photon light. With two identical pump beams counter-propagating in an optical fiber, each creates a two-photon state via SFWM. By combining the two-photon pairs together, four Bell states can be prepared with appropriate polarization and phase controls. Polarization entanglement can also be obtained.

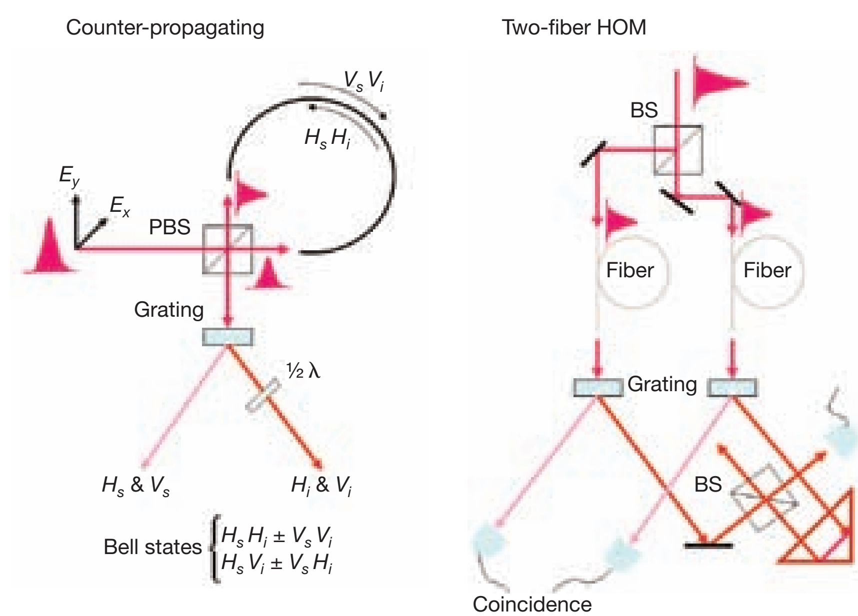
This was recently demonstrated by the Northwestern and NTT teams (Phys. Rev. Lett. **94**, 053601, Opt. Lett. **31**, 1905 and 1286, and Phys. Rev. A **72**, 041804R). Rarity and his colleagues showed Hong-Ou-Mandel (HOM) interference using the two-photon light created in SFWMs in two separate but identical optical fibers. Using the coincidence of the two signal photons as the gate, they observed HOM interference between the two idler photons after a beamsplitter.

Creation of two-photon light and Bell states through degenerate SFWM



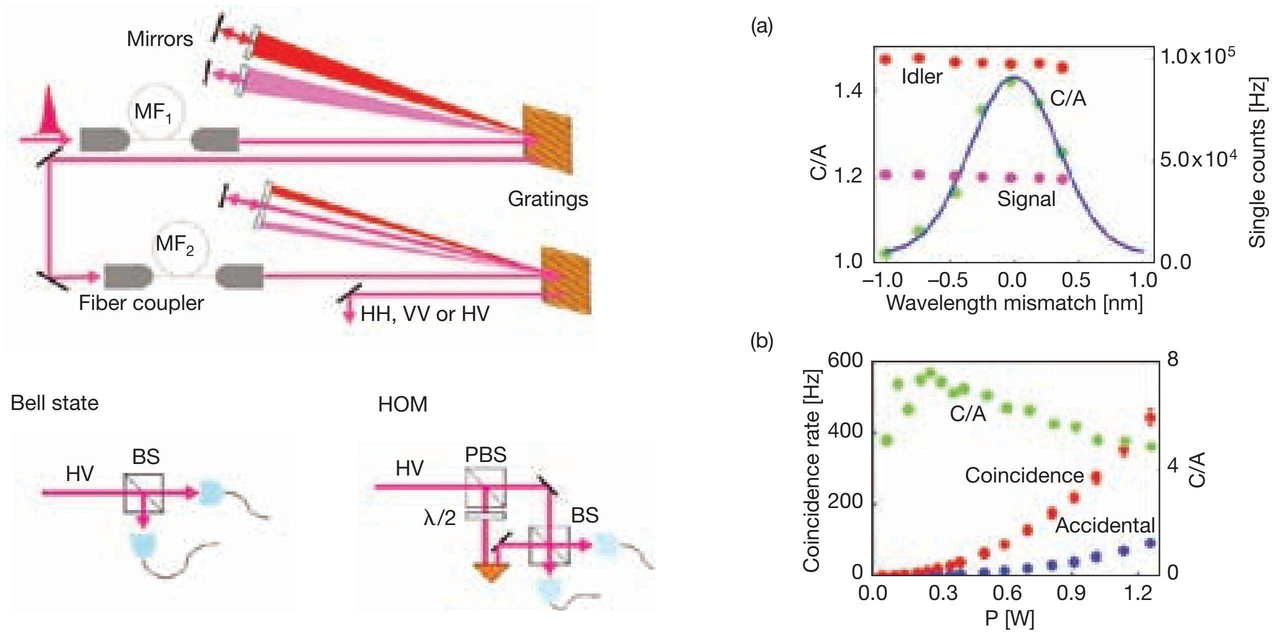
A two-pass grating configuration is used. The signal and idler photons selected by adjustable slits are focused back onto the grating, and put back into single spatial modes upon exiting the grating. They are collected into SMFs and fed into single-photon detectors. A pair of cross-polarized pump beams co-propagate in the fiber, with each beam creating a two-photon state $H_s H_i$ (or $V_s V_i$). The two photons are indistinguishable upon exiting the fiber, forming two-photon entanglement $H_s H_i + V_s V_i$. Other Bell states can be made with appropriate delay and polarization control.

Counter-propagating and two-fiber pump schemes



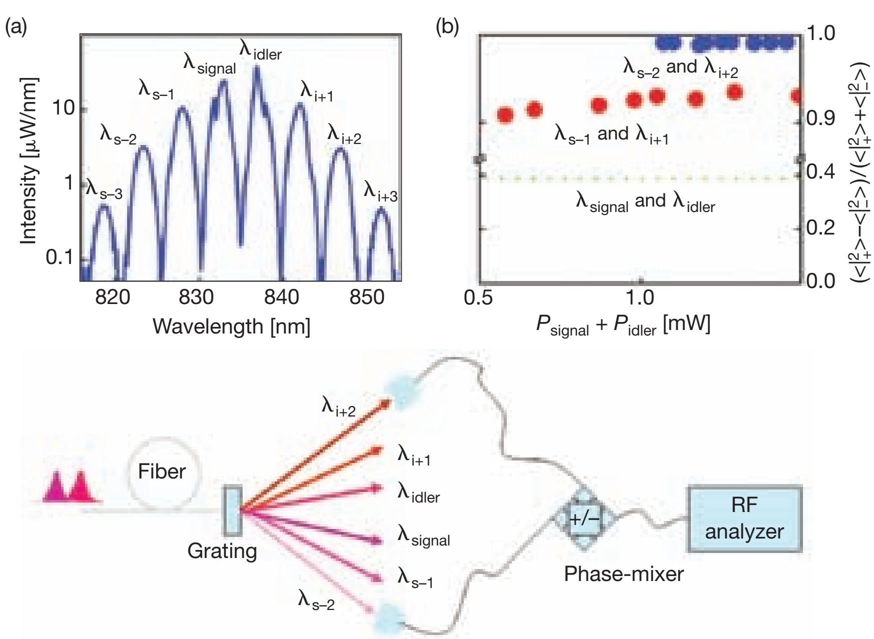
Schemes for creation of Bell states and the Hong-Ou-Mandel interference experiment. PBS: polarizing beam splitter; BS: 50/50 non-polarizing beam splitter.

Reverse degenerate SFWM with different polarization



Reverse degenerate SFWM with different polarization inputs can create the output two photons in different polarization states for post-selective Bell measurements or Hong-Ou-Mandel interference. (a) Determination of two-photon correlation in a reverse degenerate SFWM process. (b) Measurement of two-photon brightness as a function of pump power. Experiment was performed with two 1.7 m MFs (γ = 100/W/km), pumped by an 8 ps laser pulse at λ_{ZDW} =735 nm.

Setup for cascaded non-degenerate FWMs



Setup with $\omega_{signal} + \omega_{idler} = \omega_{s-1} + \omega_{i+1} = \omega_{s-2} + \omega_{i+2} = \omega_{s-2} + \omega_{i+3}$. The induced photo-currents by signal and idler beams on the photo-diodes are fed into a phase-mixer to produce $<I_+^2>$ and $<I_-^2>$ that are connected to a spectrum analyzer. (a) Measured spectrum for cascaded FWMs. (b) Measured noise cross-correlation between signal and idler beams.

Reversed degenerate SFWM

The reverse degenerate FWM process $\omega_{p_1} + \omega_{p_2} \longrightarrow \omega_{signal} + \omega_{idler}$ can also occur. Normally, when there are two or more pump wavelengths, many FWM processes can appear, but stimulated degenerate FWM dominates. In most experiments reported so far with two pump wavelengths $\omega_{p_1} < \omega_{p_2}$, the two stimulated degenerate FWM processes $2\omega_{p_1} \longrightarrow \omega_{signal} + \omega_{p_2}$ and $2\omega_{p_2} \longrightarrow \omega_{p_1} + \omega_{idler}$ have dominated over the spontaneous non-degenerate FWM process: $\omega_{p_1} + \omega_{p_2} \longrightarrow \omega_{signal} + \omega_{idler}$. Recently, we saw the dominance of this reverse degenerate FWM process, with the twin photons generated at the mean frequency being highly correlated (Opt. Lett. **30**, 1530 and 3368).

When the dispersion slowly varies near λ_{ZDW}, phase-matching or quasi-phase-matching can be easily satisfied between the pump, signal and idler fields at low power. By arranging a pair of pump beams with frequencies ($\omega_{signal} + \omega_{idler}$) conjugate with respect to λ_{ZDW}, such a

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process $\omega_{signal} + \omega_{idler} \rightarrow 2\omega_{ZDW}$ can occur and dominate. This is a reversed degenerate SFWM process.

In our experiment, we put two identical MFs in series and coupled a laser pulse into the first MF to create a broadband light pulse. The output is sent to a two-pass grating to select a pair of conjugate signal and idler pump wavelengths. This pair of pump beams is then coupled into the second MF. Using another two-pass grating arrangement, we collected only photons at λ_{ZDW}. Measurements show that this light appears mostly in pairs, indicating that non-degenerate SFWM dominates. The brightness of this two-photon light is comparable to that of SPDC.

Researchers and engineers have been consistently interested in studying the correlation between the Stokes and anti-Stokes light created by degenerate FWM with a single pump wavelength. However, no correlation studies have been made of FWM with multiple pump wavelengths; this is due to the assumption that there is no direct correlation between the Stokes and anti-Stokes beams because of the dominance of degenerate FWM amplification.

Continuing with the reverse degenerate FWM experiment, we examined the noise cross-correlation between those created twin spectral side bands that are restricted by $\omega_{signal} + \omega_{idler} = \omega_{s-1} + \omega_{i+1} = \omega_{s-2} + \omega_{i+2}$. The photo-currents induced by the signal and idler light in photodiodes are connected to a phase-mixer to produce sum- and difference-currents I_+ and I_-, which are connected to a spectrum analyzer for noise analysis. When the twin beams are perfectly correlated, $<I_-^2> = 0$. When they are completely uncorrelated, $<I_-^2> = <I_+^2>$.

Correspondingly, a classical noise correlation, defined as $(<I_+^2> - <I_-^2>)/(<I_+^2> - <I_-^2>)$, equals to 1 for perfect correlation and 0 for no correlation between the two beams, assuming equal detection efficiencies. When reverse degenerate FWM dominates at the middle frequency, we measured increased noise cross-correlation between the signal and idler beams of higher order processes. By varying the wavelength of one of the two inputs to the second fiber, we found that the measured difference-current quickly reaches to the level of the sum-current, resulting in a reduced classical noise correlation. This shows that the non-degenerate FWM dominates in the cascaded FWM processes as well.

A bright future for single photon sources

Quantum behavior of light is most profound when the light is controlled to come one photon at a time. This is true for textbook experiments, theoretical or real, as well as for real-world applications of quantum cryptography. In the past 35 years or so, researchers have developed various ways of generating one photon of light at a time. The most common methods used are variants of spontaneous parametric down-conversion (SPDC), in which a UV laser beam is typically used to generate two infrared photons at once.

Compared to an SPDC two-photon light source, an all-fiber-based two-photon light source has advantages in high spectral brightness, broad bandwidth, single spatial mode, low noise background, low collection loss, compact physical size, low pump power and compatibility with an optical network. With appropriate dispersion control, fiber-based two-photon light sources can cover the spectral range from UV to the infrared, all in a single spatial mode, meeting wavelength requirements for quantum communication and possibly other applications.

Understandably, this new technique is still in its infancy. Only a few years have passed since it was first proposed. However, it's already showing promise. With more R&D effort, particularly from the engineering aspect, it is conceivable that one day a cheap, robust, plug-and-play single-photon source will be ubiquitous in real-world cryptography systems. ▲

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