Narrowest-Linewidth Single-Mode Biphotons Generated from Room-Temperature or Hot Media

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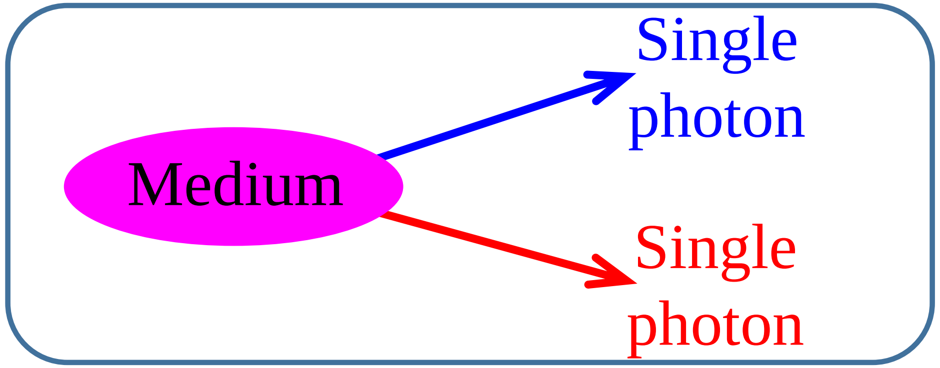
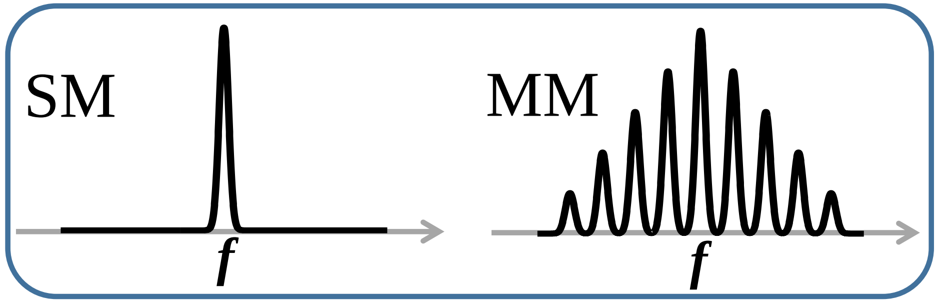
Introduction

Narrowest-Linewidth Single-Mode Biphotons Generated from Room-Temperature or Hot Media

- ✓ **“Biphoton”** is a pair of time-correlated single photons. After the first photon is detected to start or trigger a quantum operation, the second one in the same pair can be employed in the operation as a heralded qubit.



- ✓ **“Single-Mode”** means a single frequency mode as opposite to multiple frequency modes or components.

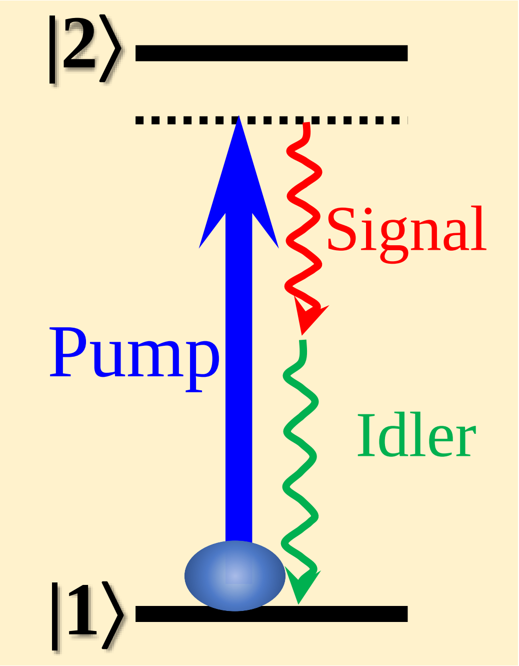


- ✓ **“Room-Temperature or Hot Media”** can be nonlinear crystals or atomic vapors, which are typically heated above RT, as opposite to cryogenic materials or cold atoms.

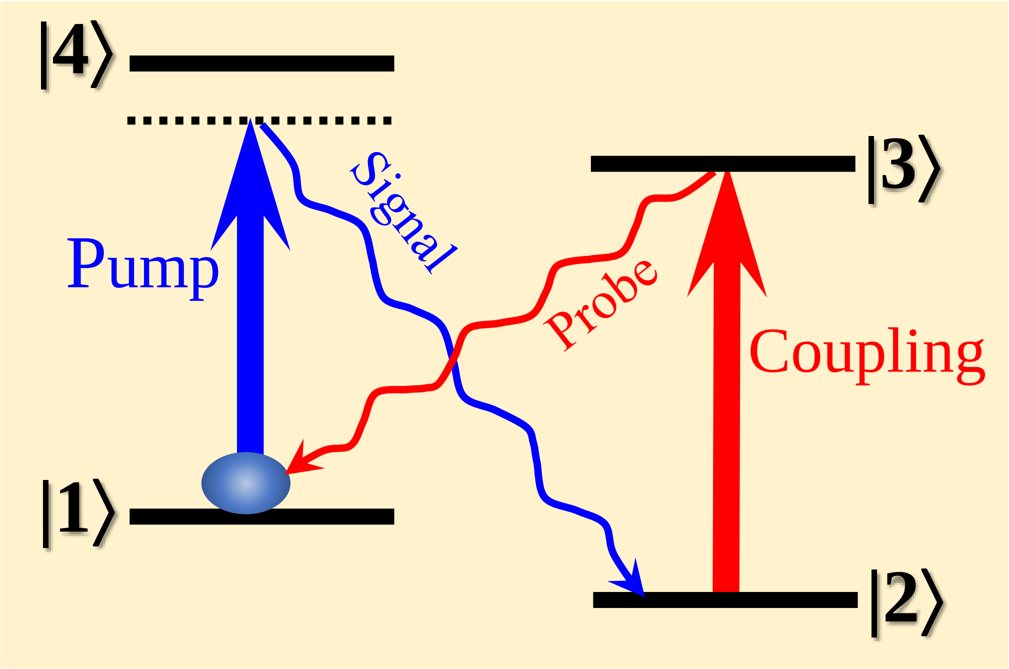
Photonic qubits of narrower linewidths can make quantum components, such as QM, QWC and QPG, have higher efficiencies or success rates.

Mechanisms for Generation of Biphotons

Spontaneous Parametric Down Conversion (SPDC)



Spontaneous Four-Wave Mixing (SFWM)



- ✓ SPDC with nonlinear crystals. The cavity-assisted SPDC biphotons can have a narrow linewidth. Depending on the cavity, SPDC can operate in either a single mode or multi-modes.
- ✓ SFWM with laser-cooled atoms or hot atomic vapors. The linewidth of the biphotons is tunable and it is limited to the decoherence rate in the system.

Comparison between Different Methods

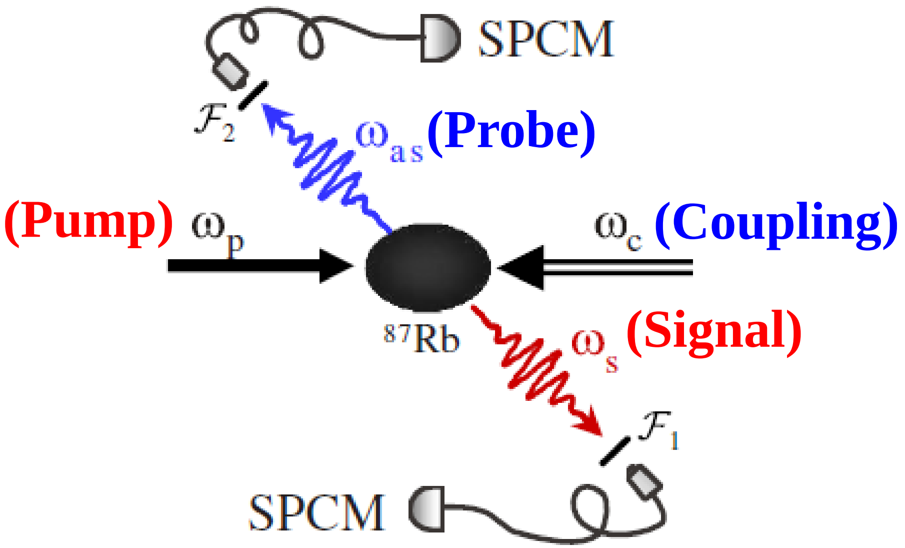
		Best Linewidth	Best Generation Rate per Linewidth	Linewidth Tunability	Frequency Tunability	Notes
Single-Mode SPDC		3 MHz[1]	3.5×10^5 pairs/s/MHz[5]	N.A.	a few GHz	
Multi-Mode SPDC		265 kHz[2]	4,300 pairs/s/MHz[6]	N.A.	a few GHz	The values refer to one of the frequency modes.
Cold-Atom SFWM		250 kHz[3]	4,700(×10%) pairs/s/MHz[7]	one order of magnitude	N.A.	Duty cycle ≤ 10%.
Hot-Atom SFWM	Earlier Works	2 MHz[4]	1.4×10^4 pairs/s/MHz[8]	one order of magnitude	600 MHz (Rb atoms, $T \approx 40°C$)	The frequency tunability is determined by width of the Doppler broadening.
	This Work	**290 kHz**	**3.3×10^5 pairs/s/MHz**			

[1] New J. Phys. 18, 123013 (2018).
[2] APL Photon. 5, 066105 (2020).
[3] Phys. Rev. A 93, 033815 (2016).
[4] Nat. Commun. 7, 12783 (2016).
[5] Phys. Rev. A 92, 063827 (2015).
[6] APL Photon. 4, 090804 (2019).
[7] Optica 1, 84 (2014).
[8] Appl. Phys. Lett. 110, 161101 (2017).

SFWM Biphotons Produced from Cold Atoms

The First SFWM Experiment

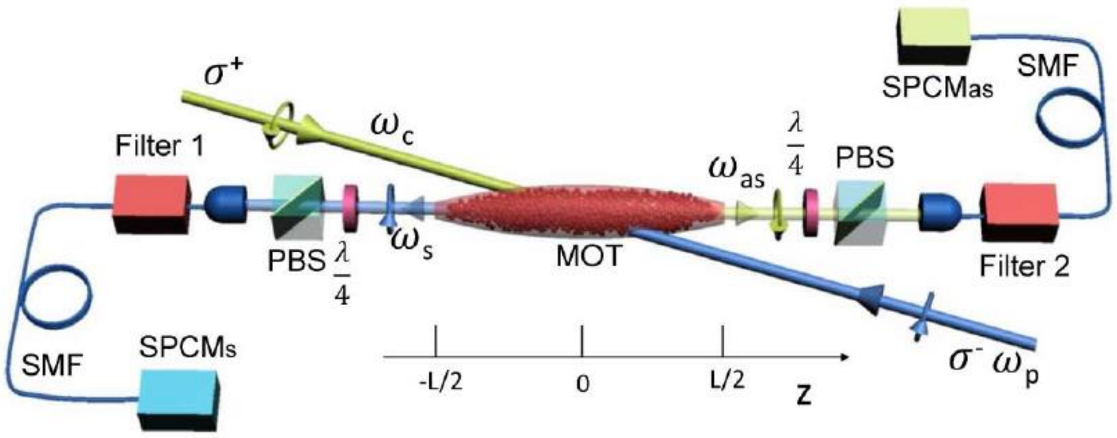
V. Balić, D. A. Braje, P. Kolchin, G. Y. Yin, and S. E. Harris, Phys. Rev. Lett. 94, 183601 (2005).



Counter propagation; angle separation of ~2°
⇒ 18 MHz; 670 (×10%) pairs/s/MHz

The Best Result to Date

L. Zhao, X. Guo, C. Liu, Y. Sun, M. M. T. Loy, and S. Du, Optica 1, 84 (2014).
L. Zhao, Y. Su, and S. Du, Phys. Rev. A 93, 033815 (2016).



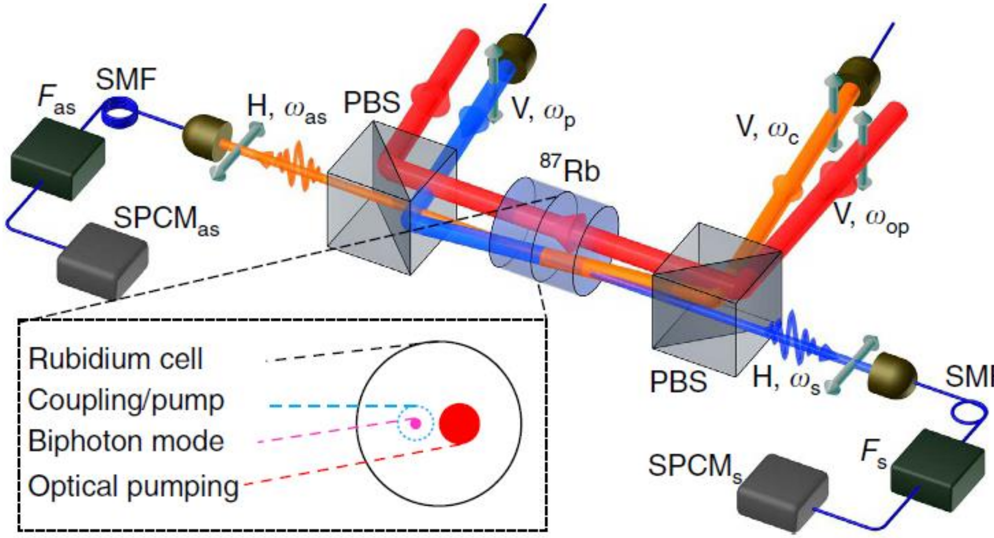
Counter propagation; angle separation of ~2.8°
⇒ 250 kHz; 4,700 (×10%) pairs/s/MHz

In literature, all the cold-atom SFWM biphoton sources utilized the counter-propagation scheme.

SFWM Biphotons Produced from Hot Atoms

The First Hot-Atom SFWM Experiment

C. Shu, P. Chen, T. K. A. Chow, L. Zhu, Y. Xiao, M. M. T. Loy, and S. Du, Nat. Commun. 7, 12783 (2016).

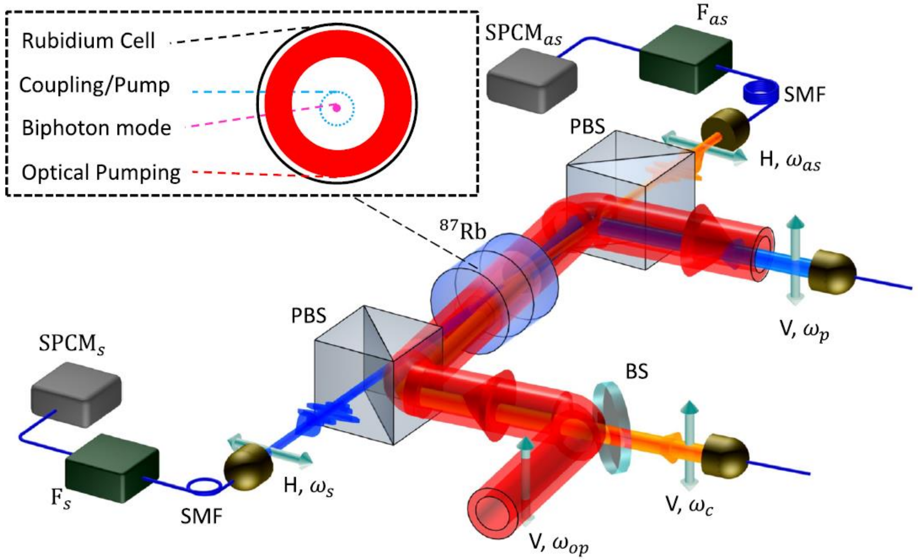


Counter propagation; angle separation of ~0.5°

⇒ 1.9 MHz; 1,000 pairs/s/MHz

The Best Result of Hot Atoms to Date

L. Zhu, X. Guo, C. Shu, H. Jeong and S. Du, Appl. Phys. Lett. 110, 161101 (2017).



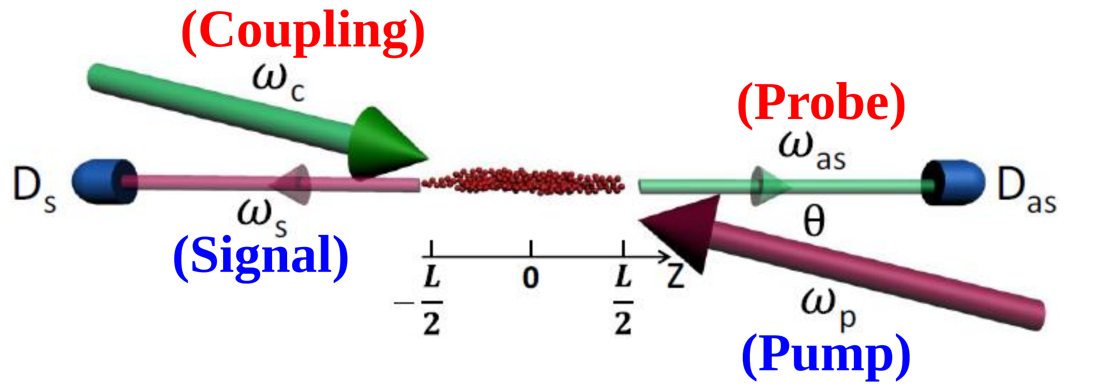
Counter propagation; angle separation of ~0.2°

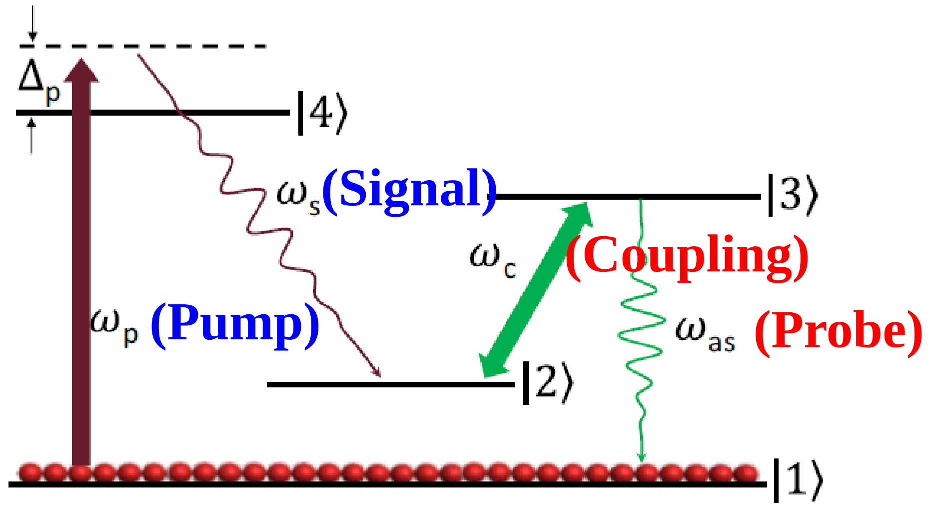
⇒ 2 MHz; 1.4×10^4 pairs/s/MHz

In literature, all the hot-atom SFWM biphoton sources utilized the counter-propagation scheme.

Phase Mismatch in the Counter-Propagation Scheme

For example: Phys. Rev. A 93, 033815 (2016).





Counter-Propagation

Two Raman Processes

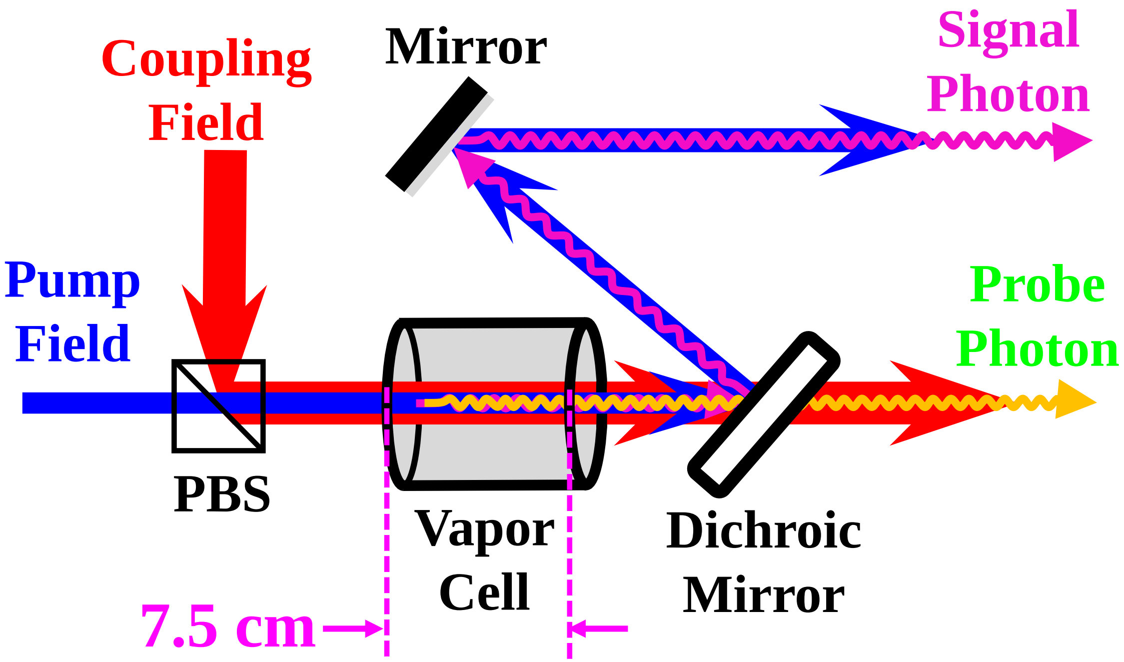
$$\Delta\vec{k} = \left(\vec{k}_{\mathrm{pump}} - \vec{k}_{\mathrm{signal}}\right) + \left(\vec{k}_{\mathrm{coupling}} - \vec{k}_{\mathrm{probe}}\right) = \left(\frac{\omega_{21}}{c}\right)(-\hat{z}) + \left(-\frac{\omega_{21}}{c}\right)\hat{z} = -\frac{2\omega_{21}}{c}\hat{z} \neq 0$$

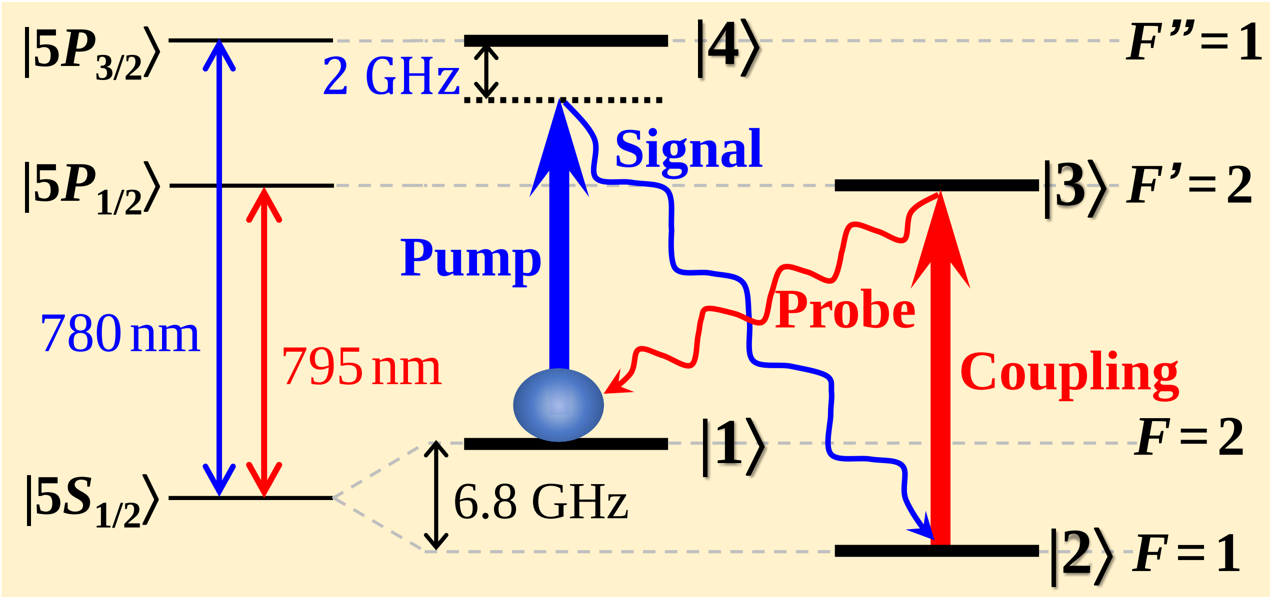
Typically, $\omega_{21} = 2\pi \times 6.8$ GHz. $\left|\Delta\vec{k}\right| = \dfrac{2\pi}{8.8\ cm}$

The degree of phase mismatch is given by $L\left|\Delta\vec{k}\right|$ (L: the medium length), which deteriorates the FWM efficiency. **The deterioration is severe for a vapor cell of a few centimeter long.**

The All-Copropagation Scheme

Experimental Setup and Transition Diagram



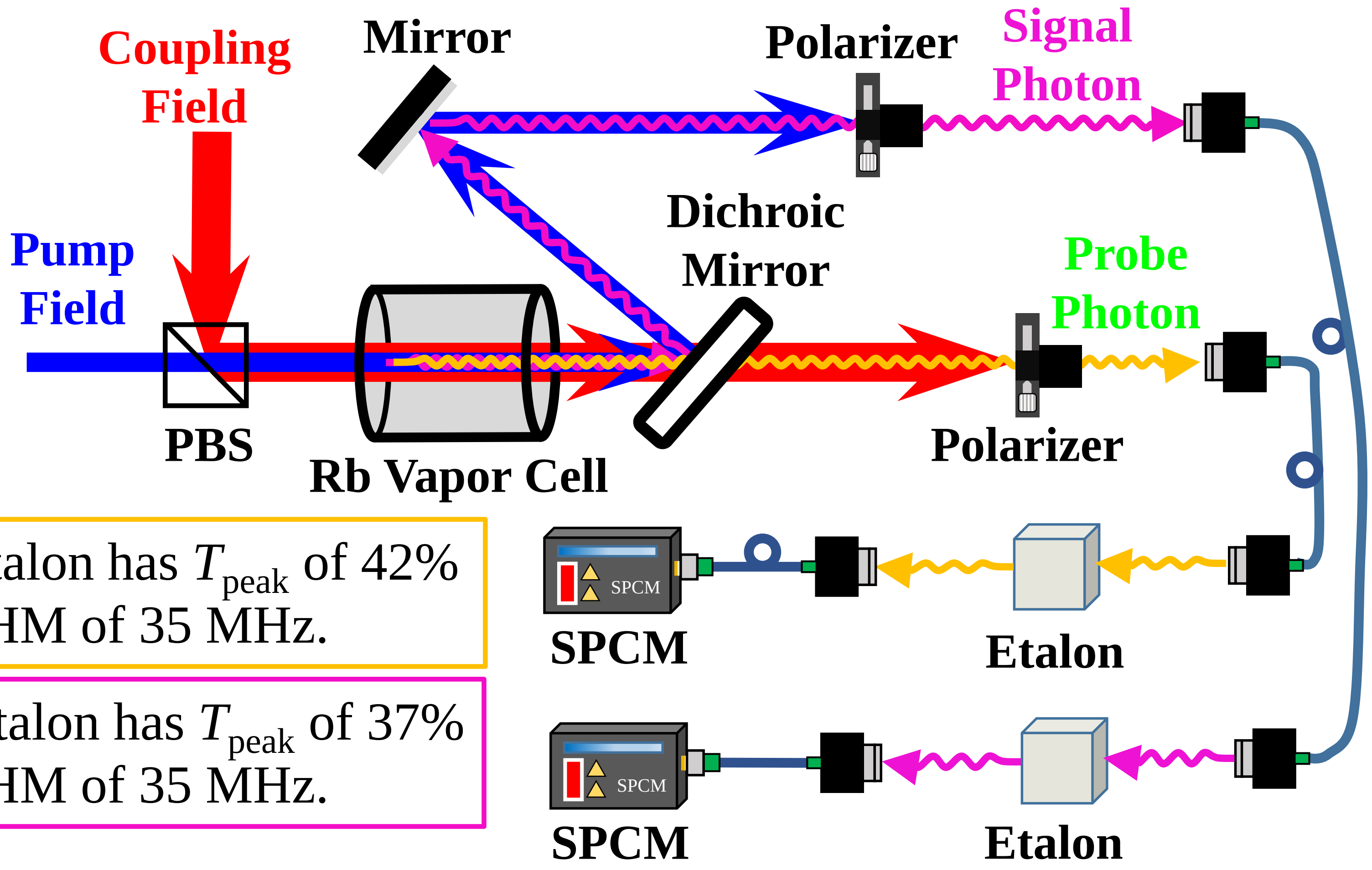


$$\Delta\vec{k} = \left(\vec{k}_{\text{pump}} - \vec{k}_{\text{signal}}\right) + \left(\vec{k}_{\text{coupling}} - \vec{k}_{\text{probe}}\right) = \left(-\frac{\omega_{12}}{c}\right)\hat{z} + \left(\frac{\omega_{12}}{c}\right)(-\hat{z}) = -\frac{2\pi}{8.8\text{ cm}}\hat{z}$$

In the counter-propagation scheme with $L = 7.5$ cm, $L\left|\Delta\vec{k}\right|$ will reduce the generation rate by 1000 folds!

The all-copropagation scheme ensures phase match, and also maintains a low decoherence rate, which enables a narrow linewidth.

Prevention of SPCM Leakages from the Pump and Coupling Fields



The polarizer provide an extinction ratio (ER) of 60 (48) dB for the pump (coupling) field.

The probe etalon has T_{peak} of 42% and the FWHM of 35 MHz.

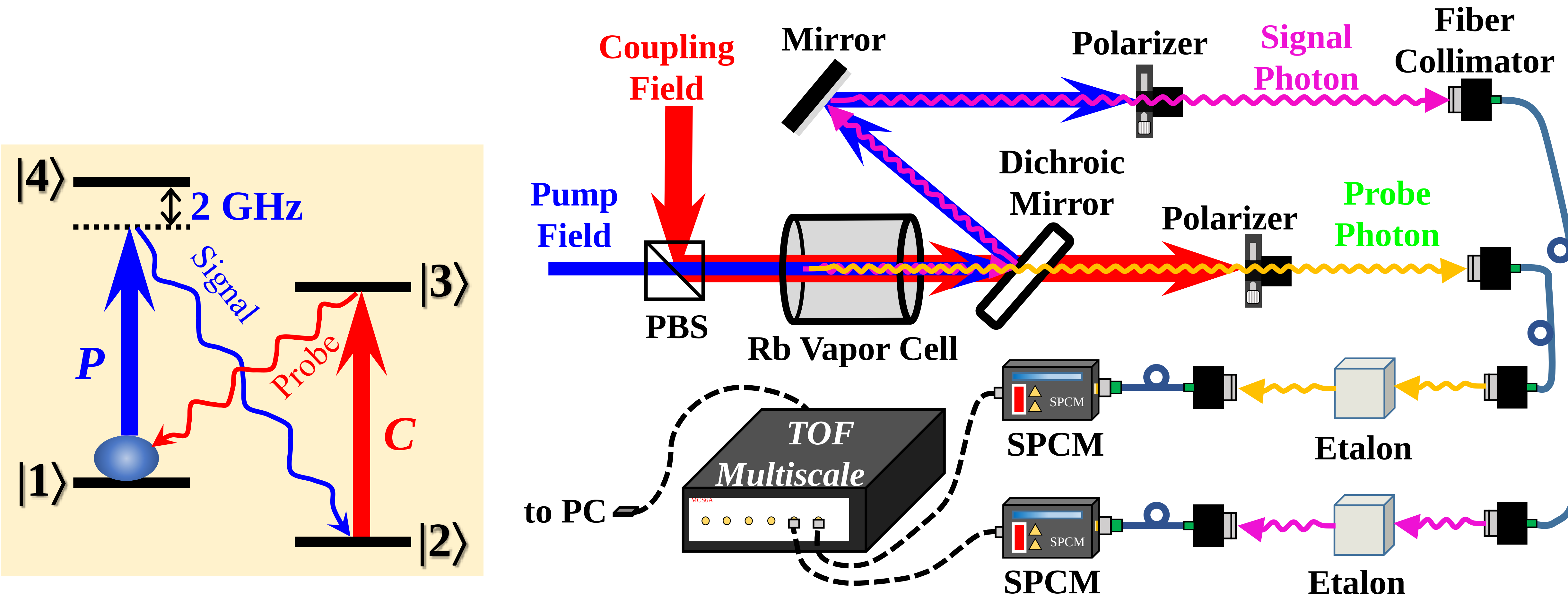
The probe etalon blocks the coupling field with an ER of 88 dB.

The signal etalon has T_{peak} of 37% and the FWHM of 35 MHz.

The signal etalon blocks the pump field with an ER of 74 dB.

- An overall ER of ~135 dB to block the strong classical light.
- The pump (coupling) field of 1 mW contributed merely ~100 (~64) counts/s or ~10^{-4} counts/μs/trigger to the SPCMs.

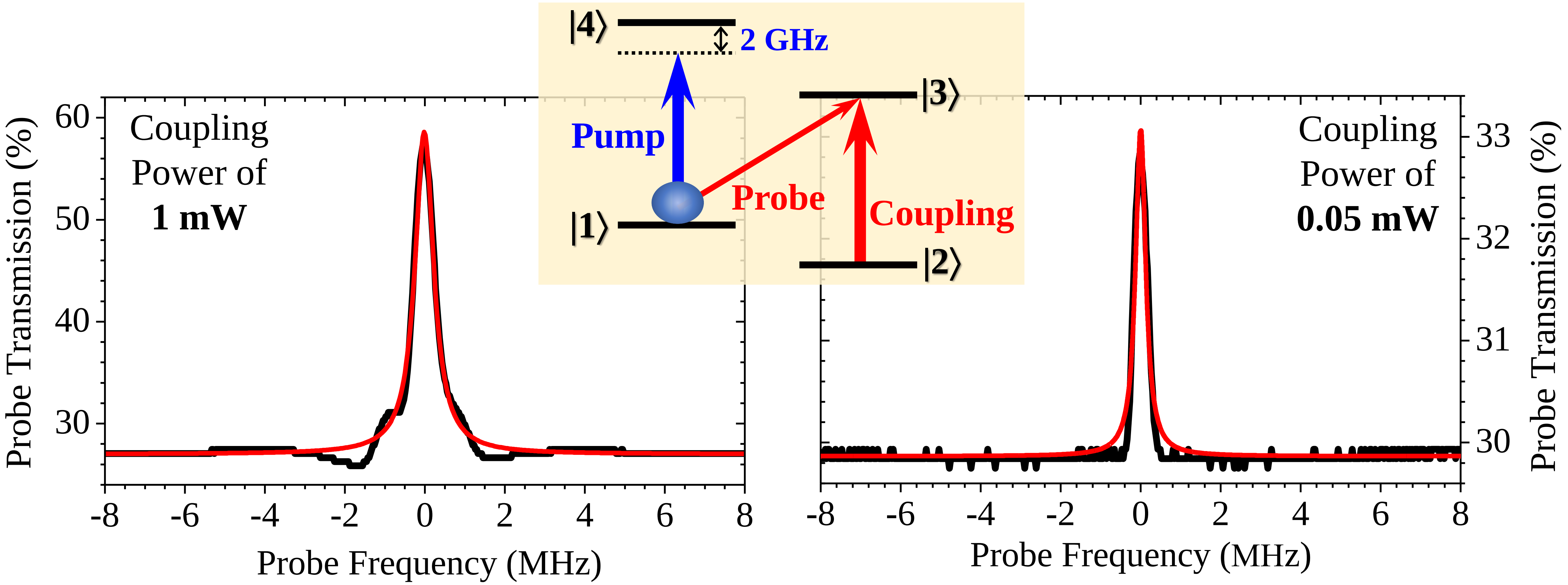
Measurement of the Biphoton (a Pair of Single Photons)



The probe photon and the coupling field form the EIT system, which predominately determines the biphoton waveform.

Experimental Data

Representative EIT Spectra Measured with Weak Classical Light

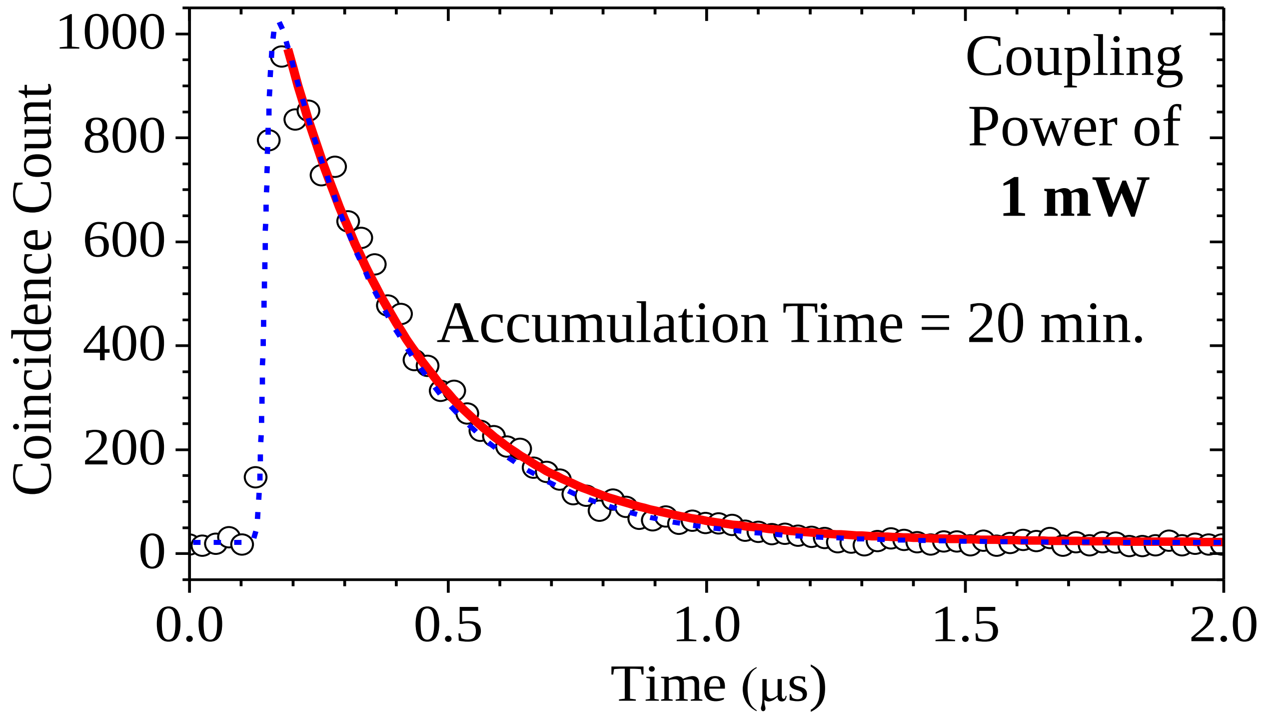


Linewidth of the Best Fit = **560 kHz**

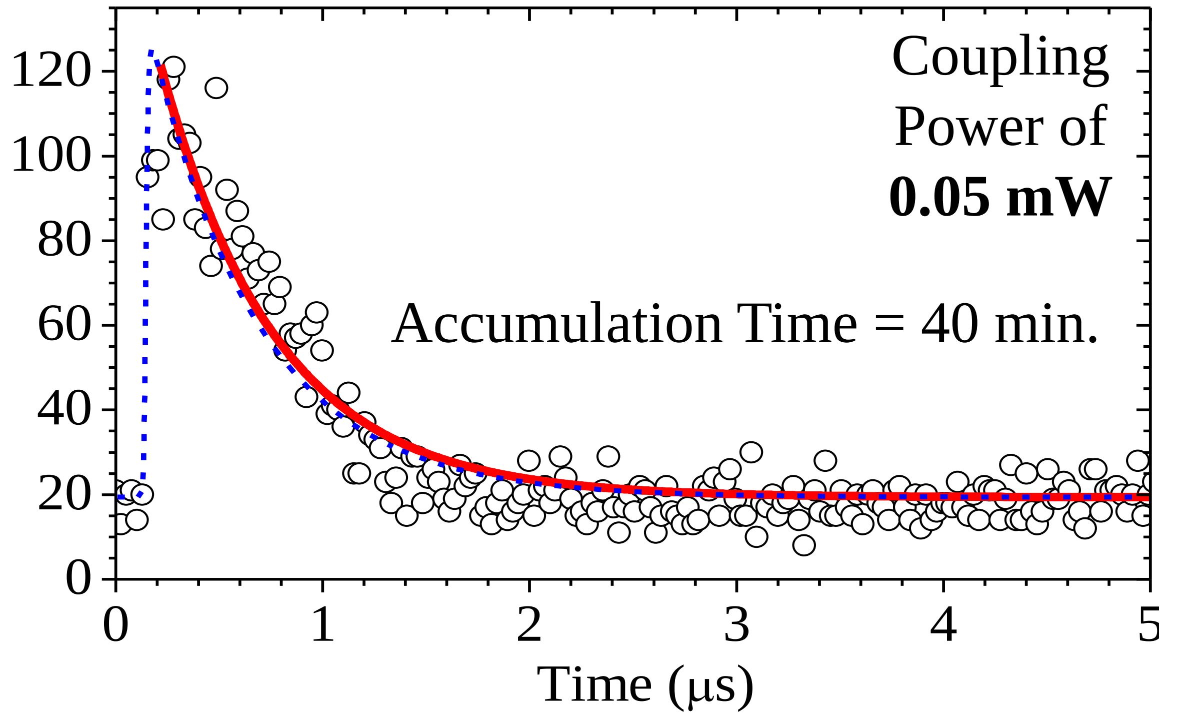
Linewidth of the Best Fit = **300 kHz**

A smaller coupling intensity results in a narrower linewidth and a smaller peak height, as expected from the theory.

Representative Data of Biphoton Waveforms $|\psi|^2$



Time Constant of the Best Fit = **0.26 μs**
Corresponding Linewidth = **610 kHz**

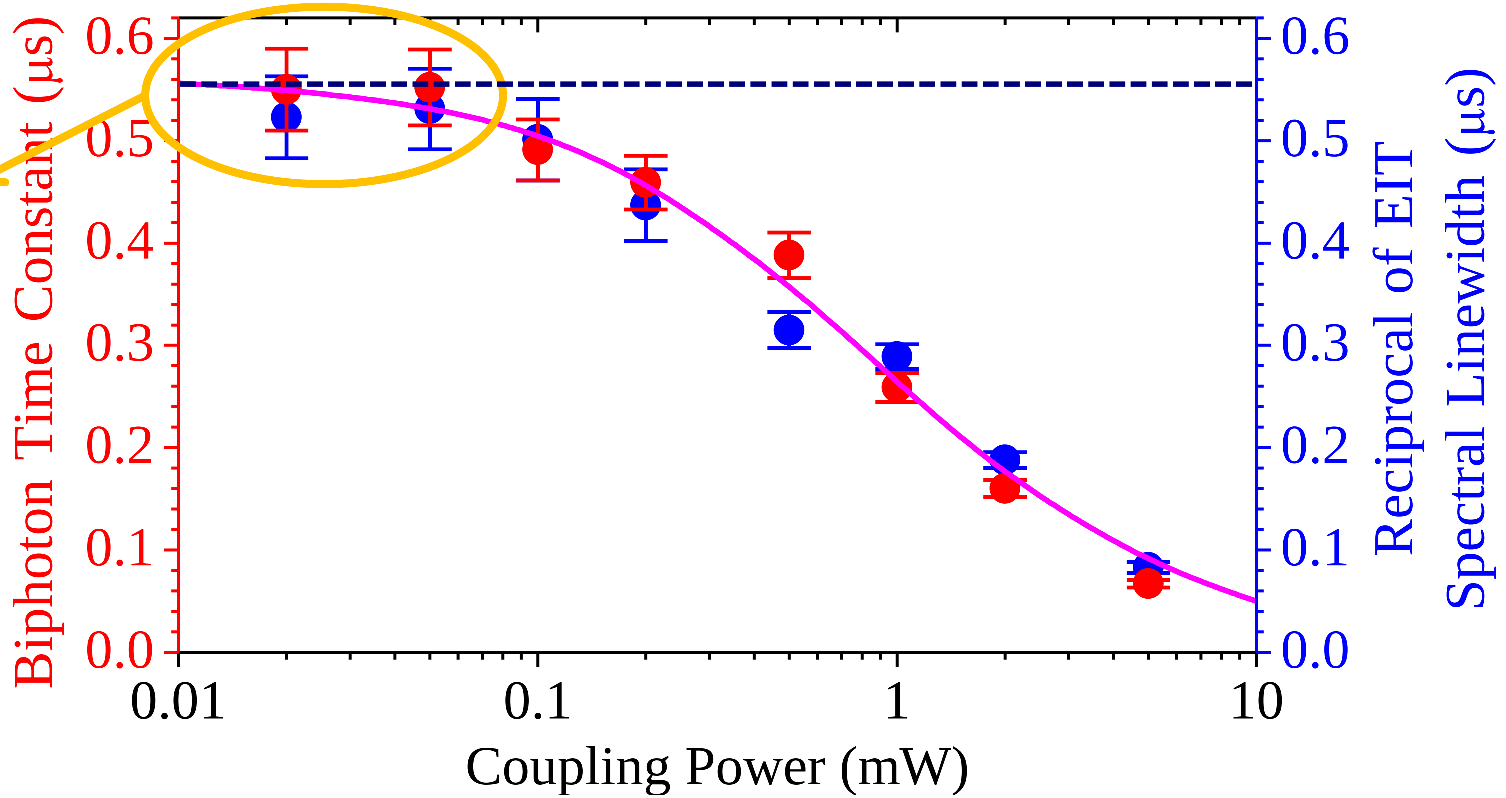


Time Constant of the Best Fit = **0.56 μs**
Corresponding Linewidth = **280 kHz**

A smaller coupling intensity results in a longer temporal width and a fewer number of coincidence counts per accumulation time, consistent with the EIT spectra.

Temporal Width of Biphoton Waveform $|\psi|^2$ and Linewidth of EIT Spectrum

550 ns or 290 kHz, **the narrowest linewidth among all single-mode biphoton sources generated from room-temperature or hot media**

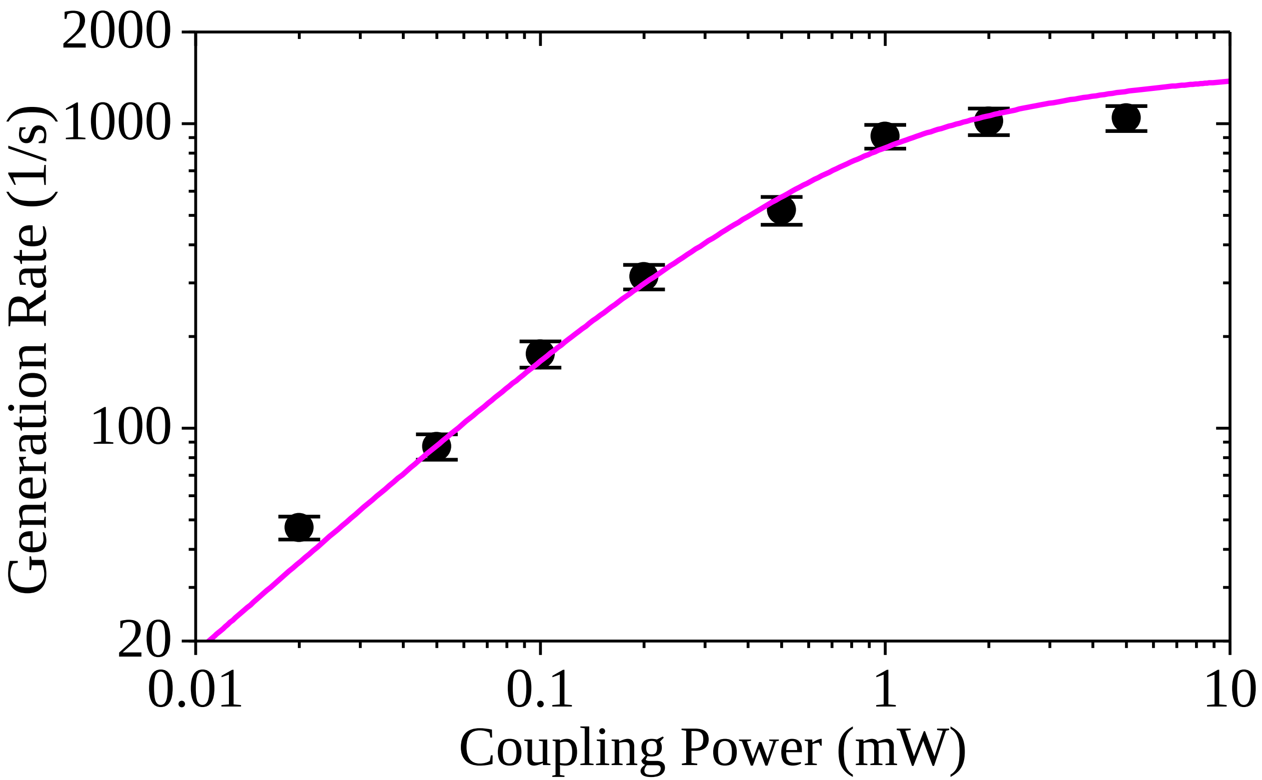


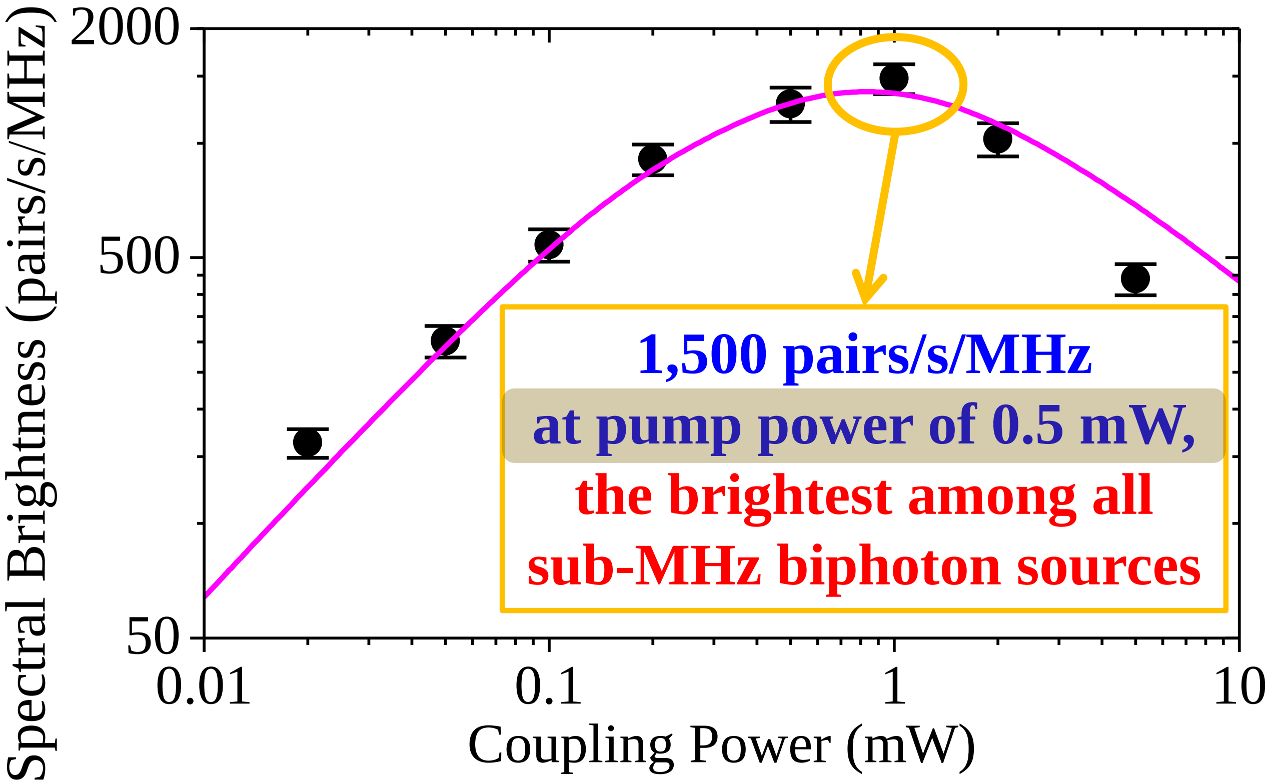
The linewidth of EIT spectrum measured with classical light can be an indicator of the temporal width of biphoton waveform.

The temporal width is limited to $(2\gamma)^{-1}$, where γ is the decoherence rate in the system.

Spectral Brightness of Biphotons versus Coupling Power

The generation rate or generation rate per linewidth (named spectral brightness) is an important figure of merit of a biphoton source.

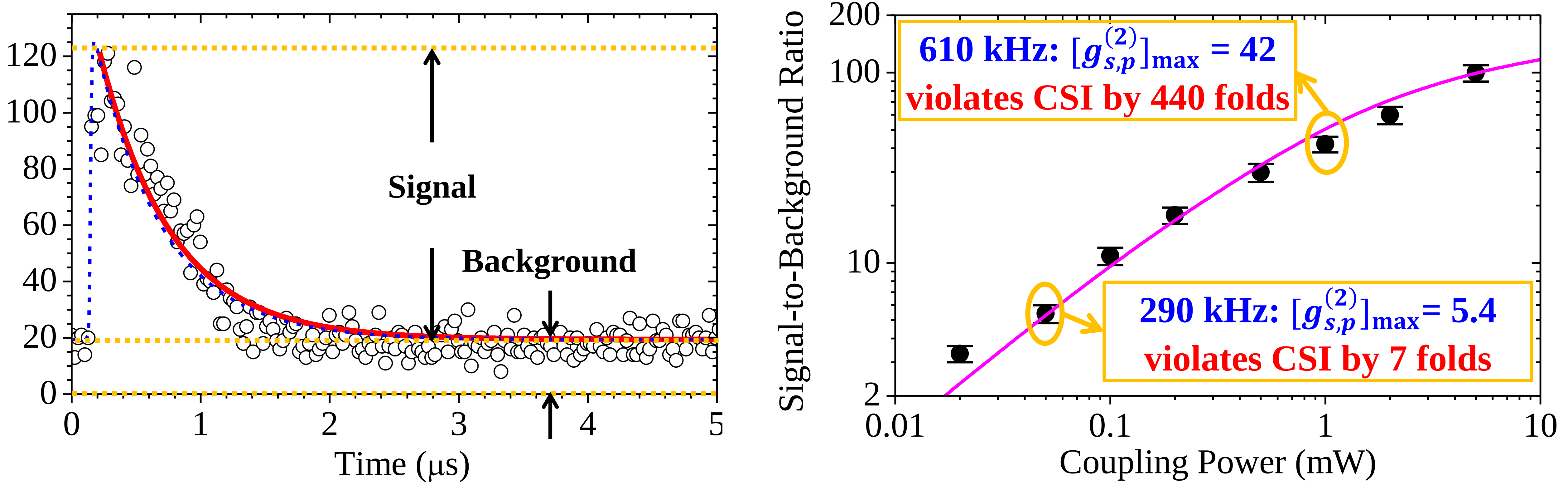




The experimental data are consistent with the theoretical predictions.

Signal-to-Background Ratio of Biphotons versus Coupling Power

The signal-to-background ratio (SBR) is another important figure of merit of a biphoton source. A larger SBR indicates that biphotons have higher purity.



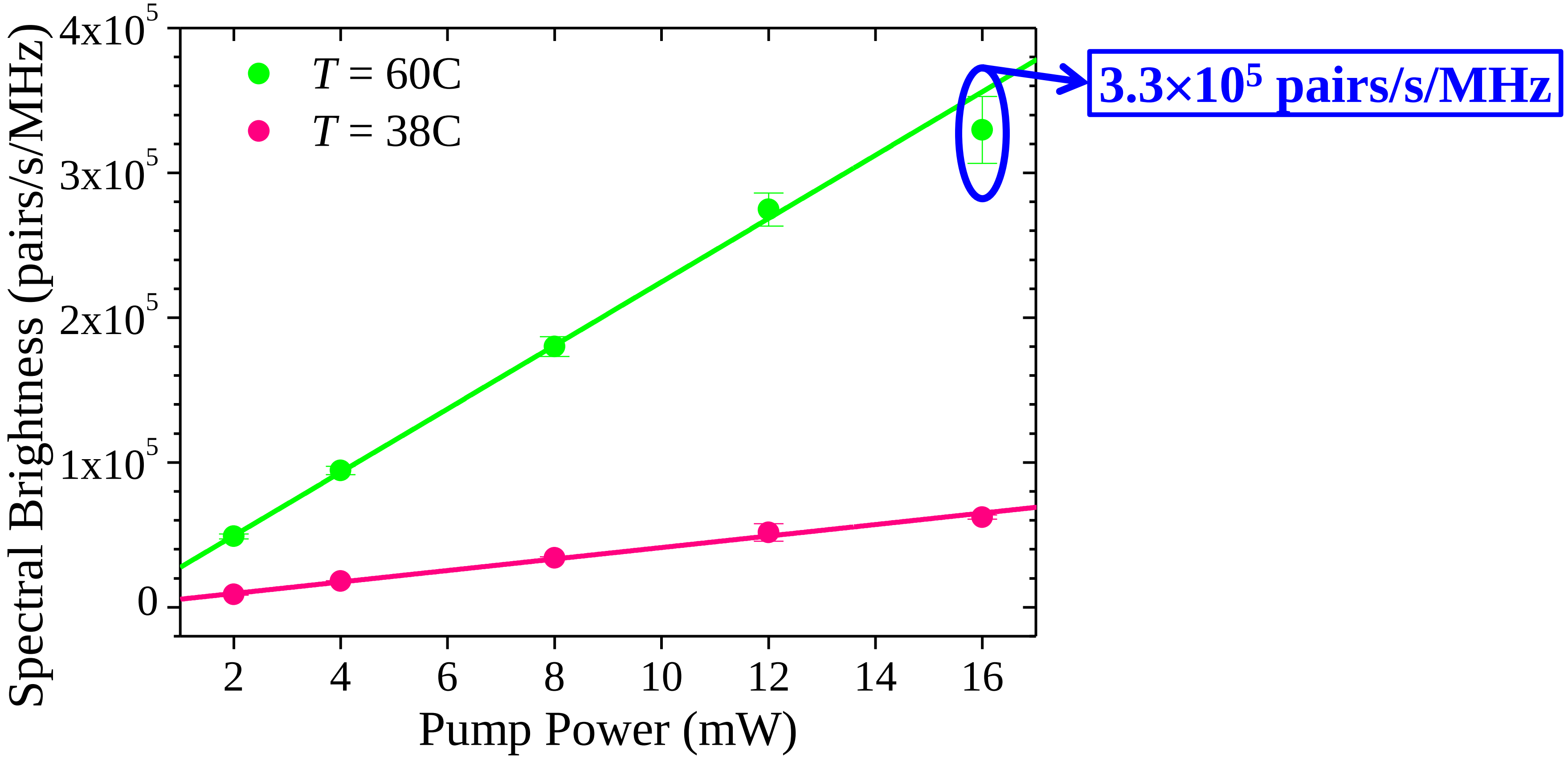
The Cauchy-Schwarz inequality (CSI) for classical light is $\left[g_{s,p}^{(2)}\right]^2 / \left[g_{s,s}^{(2)} \cdot g_{p,p}^{(2)}\right] \leq 1.$

$[g_{s,p}^{(2)}]_{\max}$ (the maximum cross-correlation function) ≈ SBR. $g_{s,s}^{(2)} \approx 2 \approx g_{p,p}^{(2)}$ (the auto-correlation function).

Spectral Brightness versus Pump Power and Temperature

The generation rate or spectral brightness can be enhanced by increasing the pump power or the vapor cell temperature at the expense of the SBR being reduced.

The linewidth of biphotons is maintained at 850 kHz.

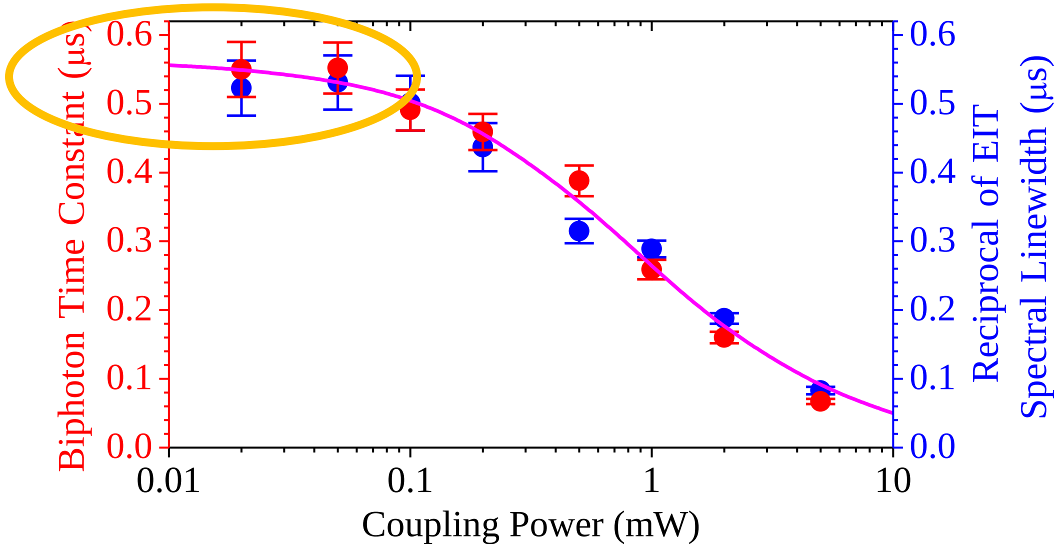


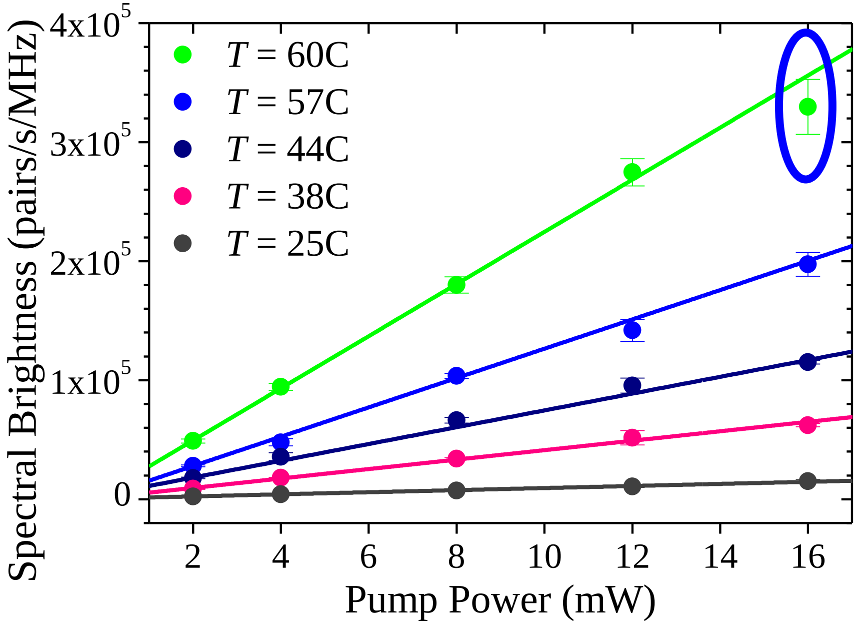
Spectral brightness of our sub-MHz biphotons is comparable with those of SPDC biphotons.

Conclusion and Prospects

Conclusion

- The linewidth of our biphotons can be as narrow as 290 kHz, which is the narrowest among all kinds of biphotons generated from room-temperature or hot media.
- The spectral brightness of our 850-kHz biphoton source can be as high as 3.3×10^5 pairs/s/MHz, which is comparable to the highest spectral brightness of all biphoton sources.
- Our biphoton source not only surpasses the sources produced with the hot-atom SFWM in the previous works, but also competes with the sources produced with the cold-atom SFWM or cavity-assisted SPDC.





Prospects

- Biphotons are pairs of time-correlated single photons and can be employed as heralded photonic qubits in long-distance quantum communication.
- The biphoton source of hot-atom SFWM possesses the merits of (1) a linewidth tunable for more than an order of magnitude and (2) being capable to set to any frequency in a continuous range of 0.6 GHz or larger.
- The all-copropagation scheme demonstrated here can maintain the phase-match condition. Thus, we believe the all-copropagation scheme will become the standard hot-atom SFWM method.

C.-Y. Hsu, Y.-S. Wang, J.-M. Chen, F.-C. Huang, Y.-T. Ke, E. K. Huang, W. Hung, K.-L. Chao, S.-S. Hsiao, Y.-H.Chen, C.-S. Chuu, Y.-C. Chen, Y.-F. Chen, I. A. Yu, "Generation of sub-MHz and spectrally-bright biphotons from hot atomic vapors with a phase mismatch-free scheme," Opt. Express 29, 4632 (2021). [Editors' Pick]

http://atomcool.phys.nthu.edu.tw/

Thank you for your attention