Highly Correlated Ultrabright Biphotons via Spontaneous Four-Wave Mixing

Jiun-Shiuan Shiu[1,2,*], Zi-Yu Liu[1,2], Chin-Yao Cheng[1,2], Yu-Chiao Huang[1,2], Ite A. Yu[3,4], Ying-Cheng Chen[5],
Chih-Sung Chuu[3,4], Che-Ming Li[2,6], Shiang-Yu Wang[7], Yong-Fan Chen[1,2]

[1]*Department of Physics, National Cheng Kung University, Tainan, Taiwan*
[2]*Center for Quantum Frontiers of Research & Technology, Tainan, Taiwan*
[3]*Center for Quantum Science and Technology, National Tsing Hua University, Hsinchu, Taiwan*
[4]*Department of Physics, National Tsing Hua University, Hsinchu, Taiwan*
[5]*Institute of Atomic and Molecular Sciences, Academia Sinica, Taipei, Taiwan*
[6]*Department of Engineering Science, National Cheng Kung University, Tainan, Taiwan*
[7]*Institute of Astronomy and Astrophysics, Academia Sinica, Taipei, Taiwan*

[*]E-mail: jsshiu@phys.ncku.edu.tw

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國立成功大學物理學系

Quantum Optics
LABORATORY
量子光學實驗室

Abstract

The pairing ratio, a metric quantifying a biphoton source's ability to generate correlated photon pairs, is crucial for assessing source quality. Despite theoretical predictions, the intrinsic characteristic of the pairing ratio has remained largely unexplored in experiments. In this study, we present experimental findings on the pairing ratio using a double-Λ spontaneous four-wave mixing biphoton source in cold atoms. At an optical depth (OD) of 20, we achieved an ultrahigh biphoton generation rate, reaching up to 1.3 × 10^7 per second, with a successful pairing ratio of 61%. Increasing the OD to 120 significantly improved the pairing ratio to 89%, while maintaining a consistent biphoton generation rate. This dual achievement, characterized by high generation rates and robust biphoton pairing, holds great promise for enhancing efficiency in quantum communication and information processing. Furthermore, in a scenario with a lower biphoton generation rate of 5.0 × 10^4 per second, we attained an impressive signal-to-background ratio of 241 for the biphoton wavepacket, surpassing the Cauchy-Schwarz criterion by approximately 1.5 × 10^4 times.

Experiment and Theory

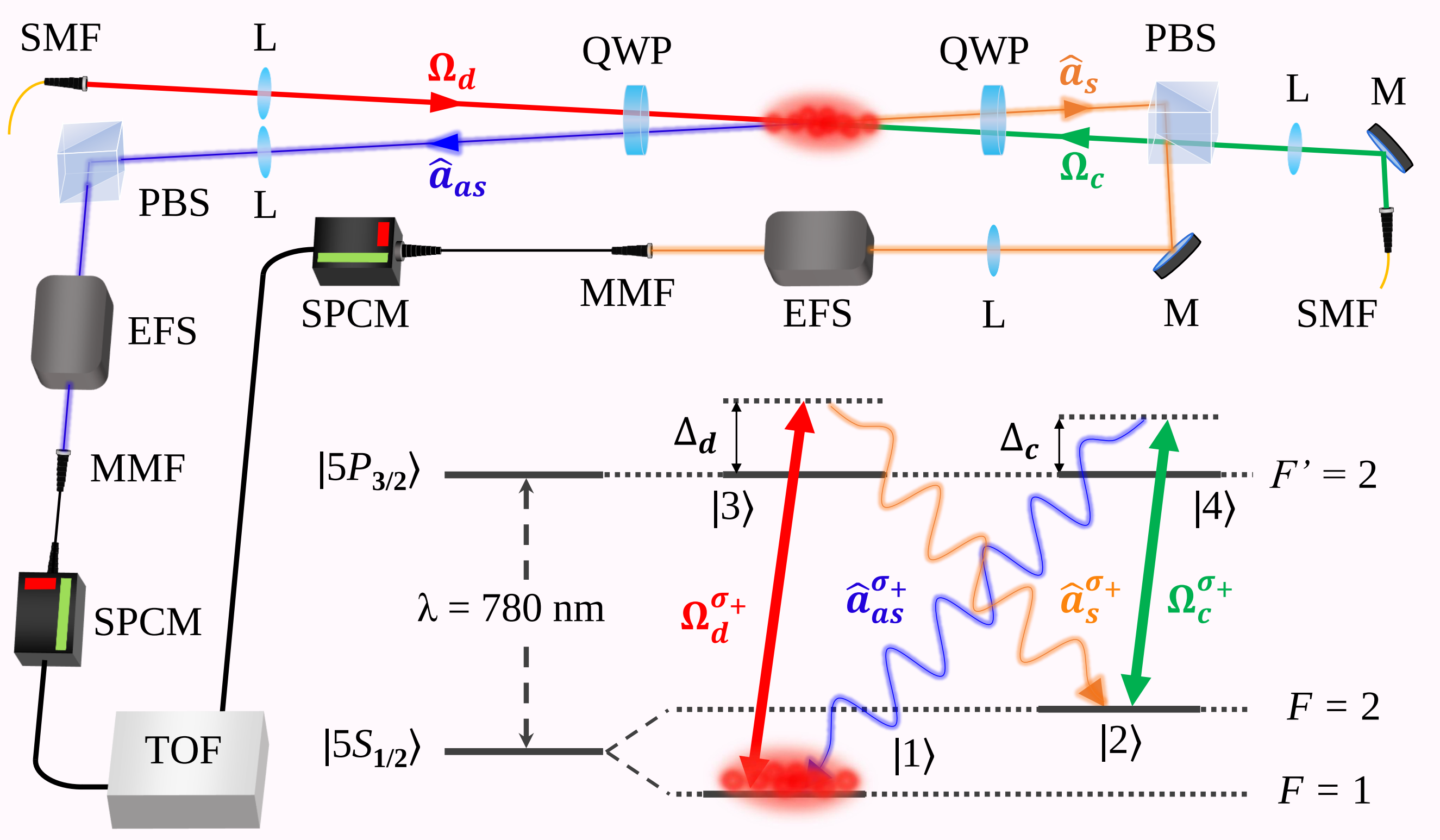


FIG. 1. Diagram of the double-Λ SFWM system and experimental setup.

Stokes and anti-Stokes photon generation rates:

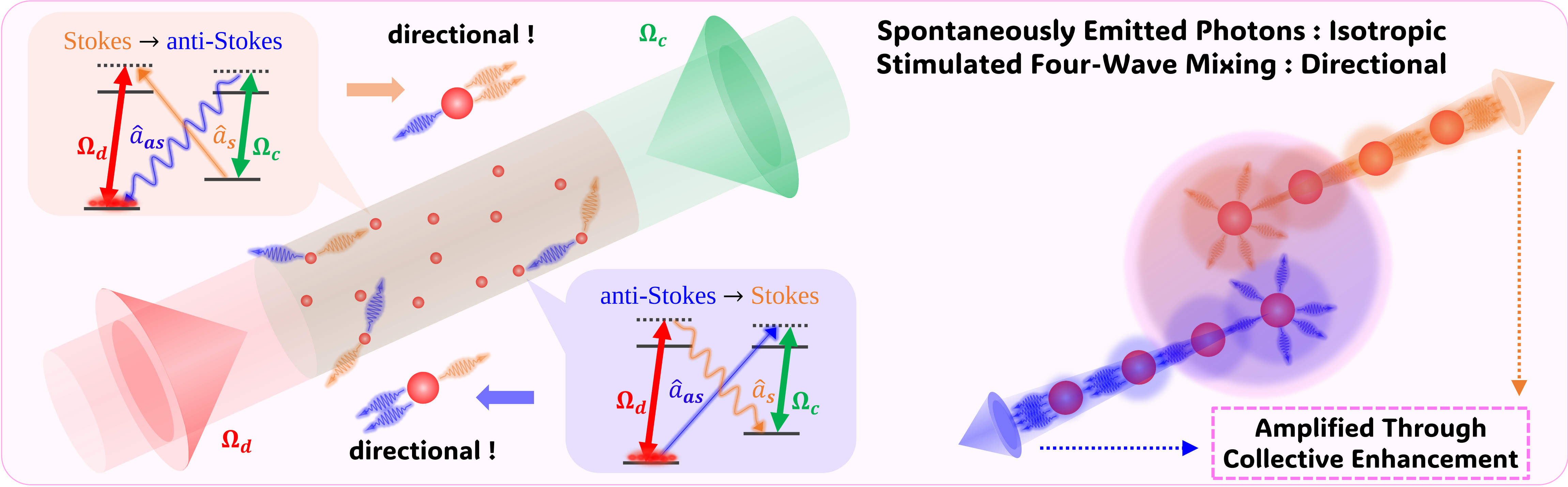
$$R_s = \frac{c}{L}\langle \hat{a}_s^{\dagger}(t)\hat{a}_s(t)\rangle = \int \frac{d\omega}{2\pi}\left(|B|^2 + \sum_{jk,j'k'}\int_0^L dz\, P_{jk}^{*}\mathcal{D}_{jk^{\dagger},j'k'}P_{j'k'}\right),$$

$$R_{as} = \frac{c}{L}\langle \hat{a}_{as}^{\dagger}(t)\hat{a}_{as}(t)\rangle = \int \frac{d\omega}{2\pi}\left(|C|^2 + \sum_{jk,j'k'}\int_0^L dz\, Q_{jk}\mathcal{D}_{jk,j'k'^{\dagger}}Q_{j'k'}^{*}\right).$$

Coincidence count rate:

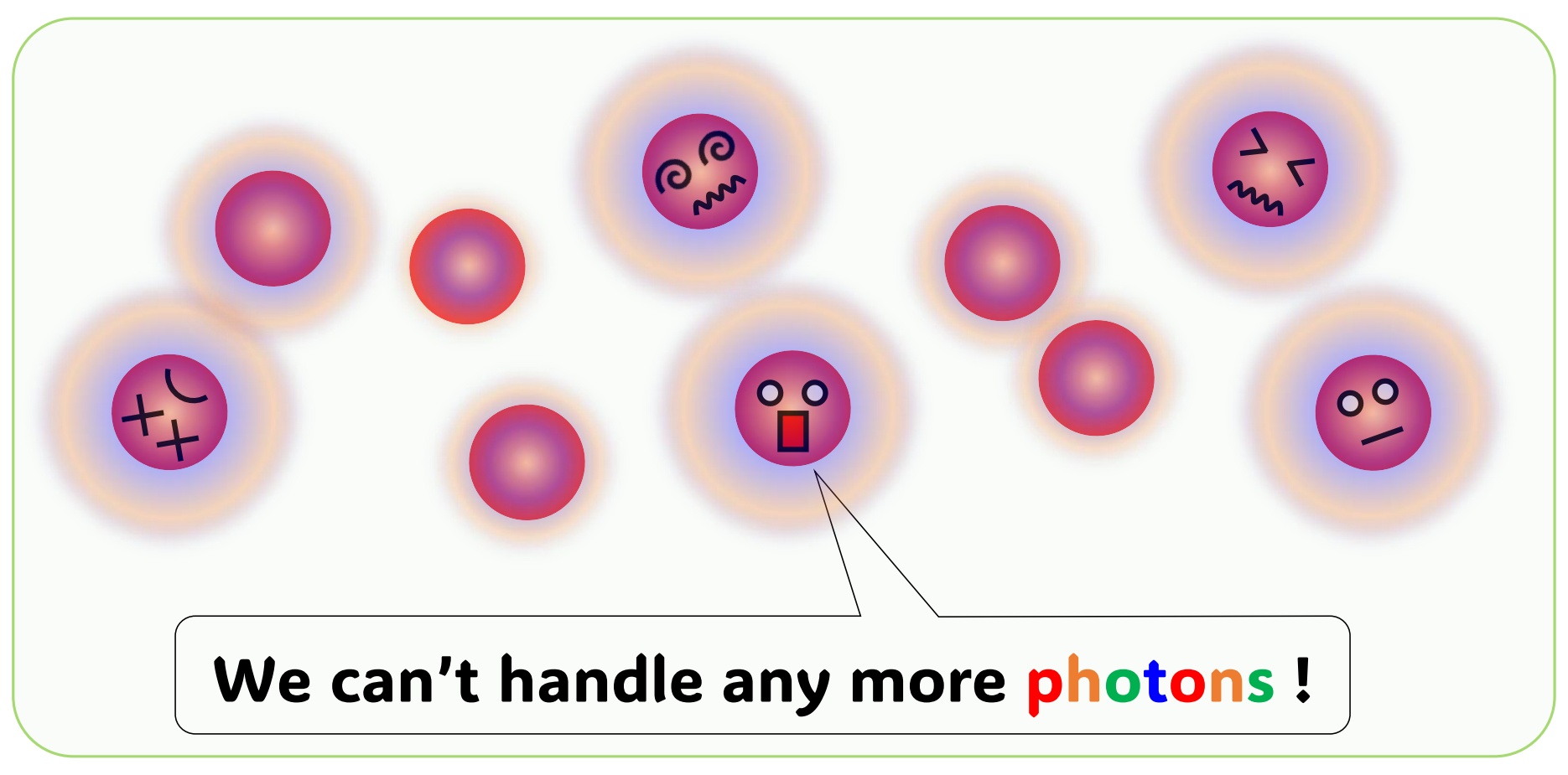
$$R_{\mathrm{C}}(\tau) = R_{as} + \frac{1}{R_s}\left|\int \frac{d\omega}{2\pi}e^{-i\omega\tau}\left(B^{*}D + \sum_{jk,j'k'}\int_0^L dz\, P_{jk}^{*}\mathcal{D}_{jk^{\dagger},j'k'}Q_{j'k'}\right)\right|^2.$$

The above results are obtained by using the same Heisenberg-Langevin operator approach as in Ref. [1], and more theoretical and experimental details are described in our recent paper [2, 3].

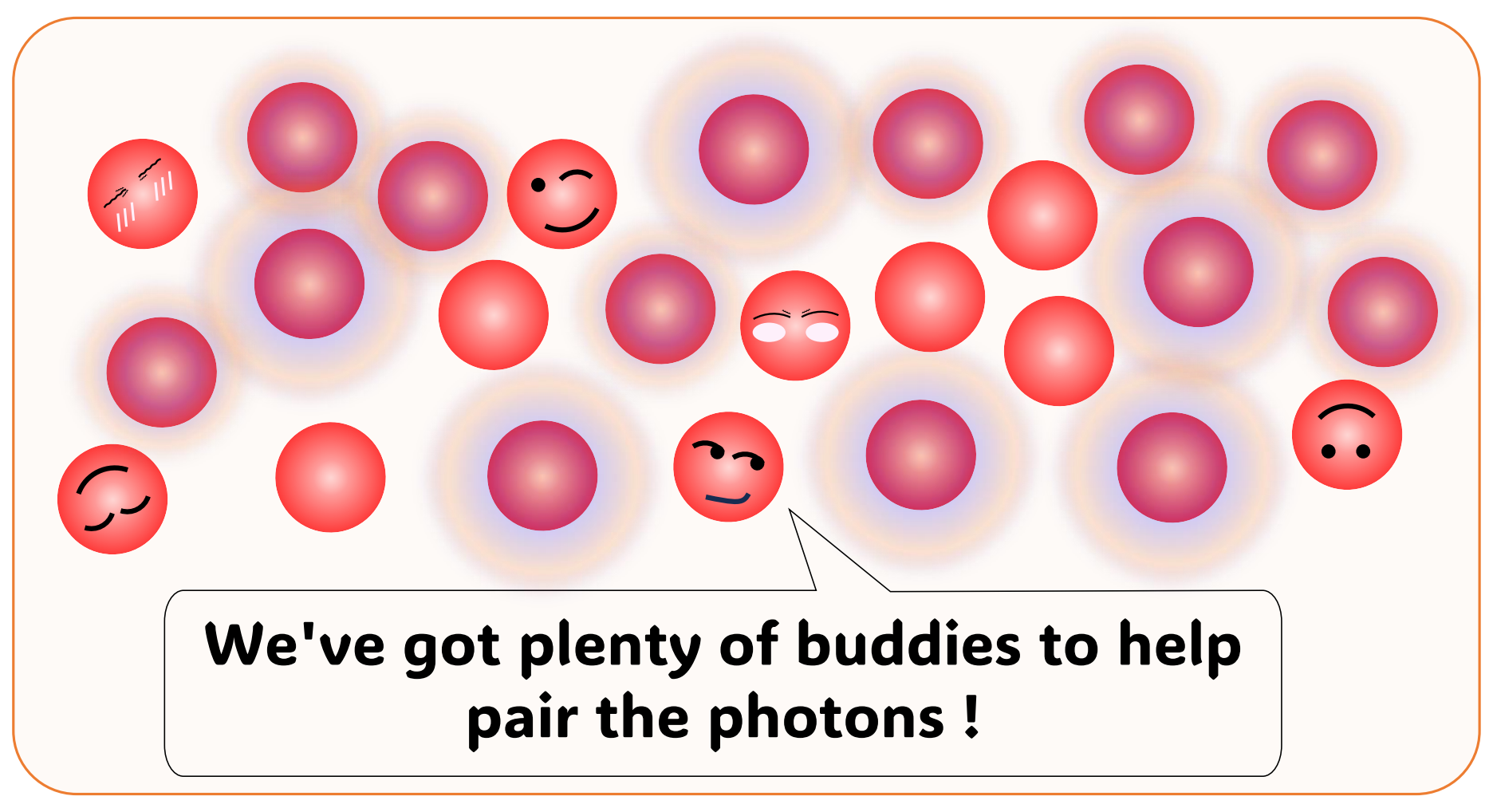


Spontaneously Emitted Photons : Isotropic
Stimulated Four-Wave Mixing : Directional

Amplified Through Collective Enhancement



We can't handle any more photons !



We've got plenty of buddies to help pair the photons !

High-Purity Biphotons

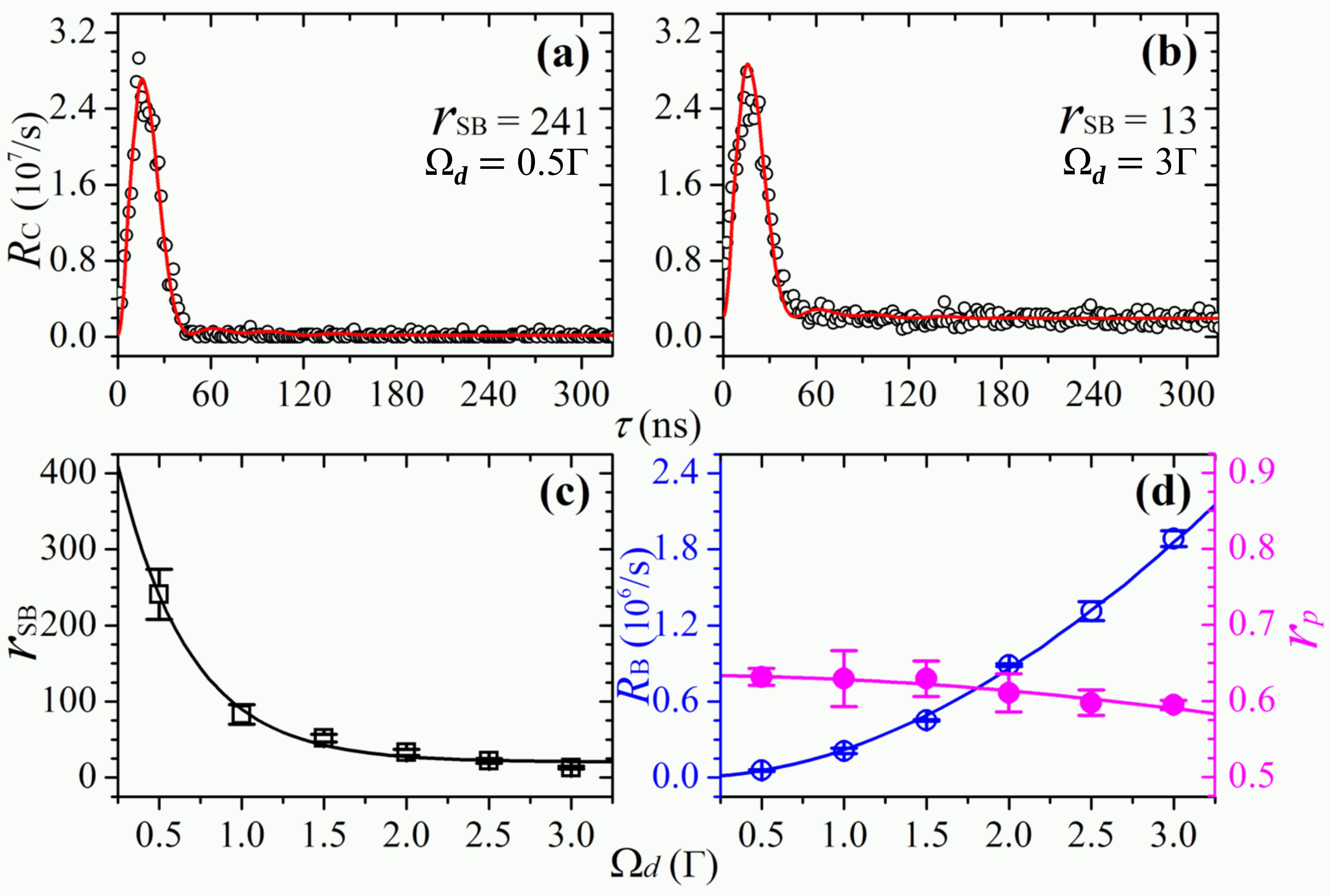


FIG. 5. High-purity biphotons. Parameters: OD = 10, Ω_c = 4Γ, Δ_d = 10Γ, with (a) Ω_d = 0.5Γ and (b) Ω_d = 3Γ. (c) The peak signal-to-background ratio r_{SB} versus Ω_d. (d) The biphoton generation rate R_B (≡ R_{as}) and pairing ratio r_p as a function of Ω_d.

Frequency-Tunable Biphotons

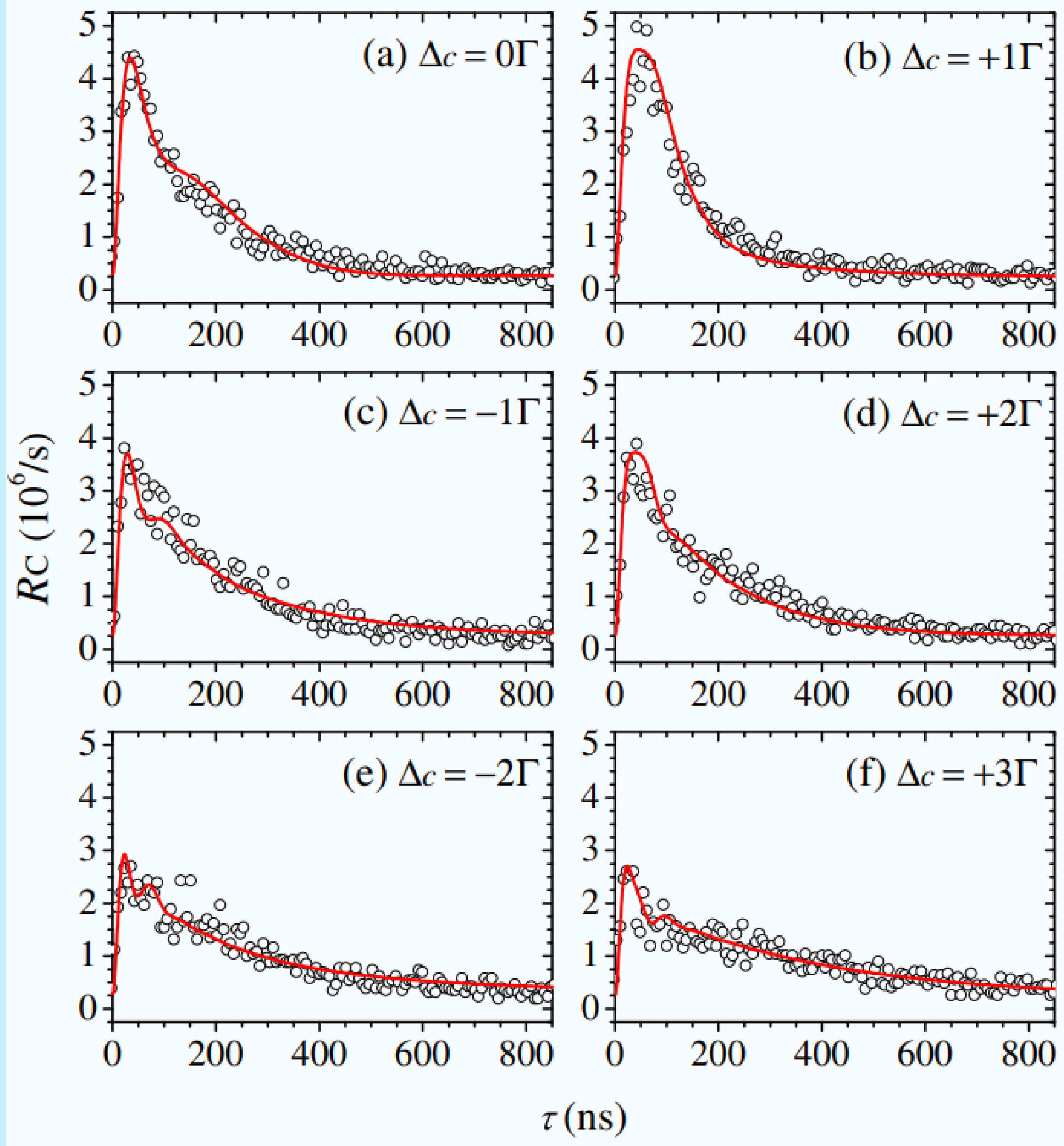


Fig. 2. Temporal profile of frequency-tunable biphotons with the coupling Rabi frequency Ω_c = 1Γ. The red lines represent the theoretical curves, while the black circles indicate the experimental data points. The other parameters are optical depth OD = 10, driving Rabi frequency Ω_d = 1Γ, driving detuning Δ_d = 10Γ, ground-state decoherence rate of γ_{21} = 0.001Γ, and phase-mismatching value of Δ*kL* = 0.37π.

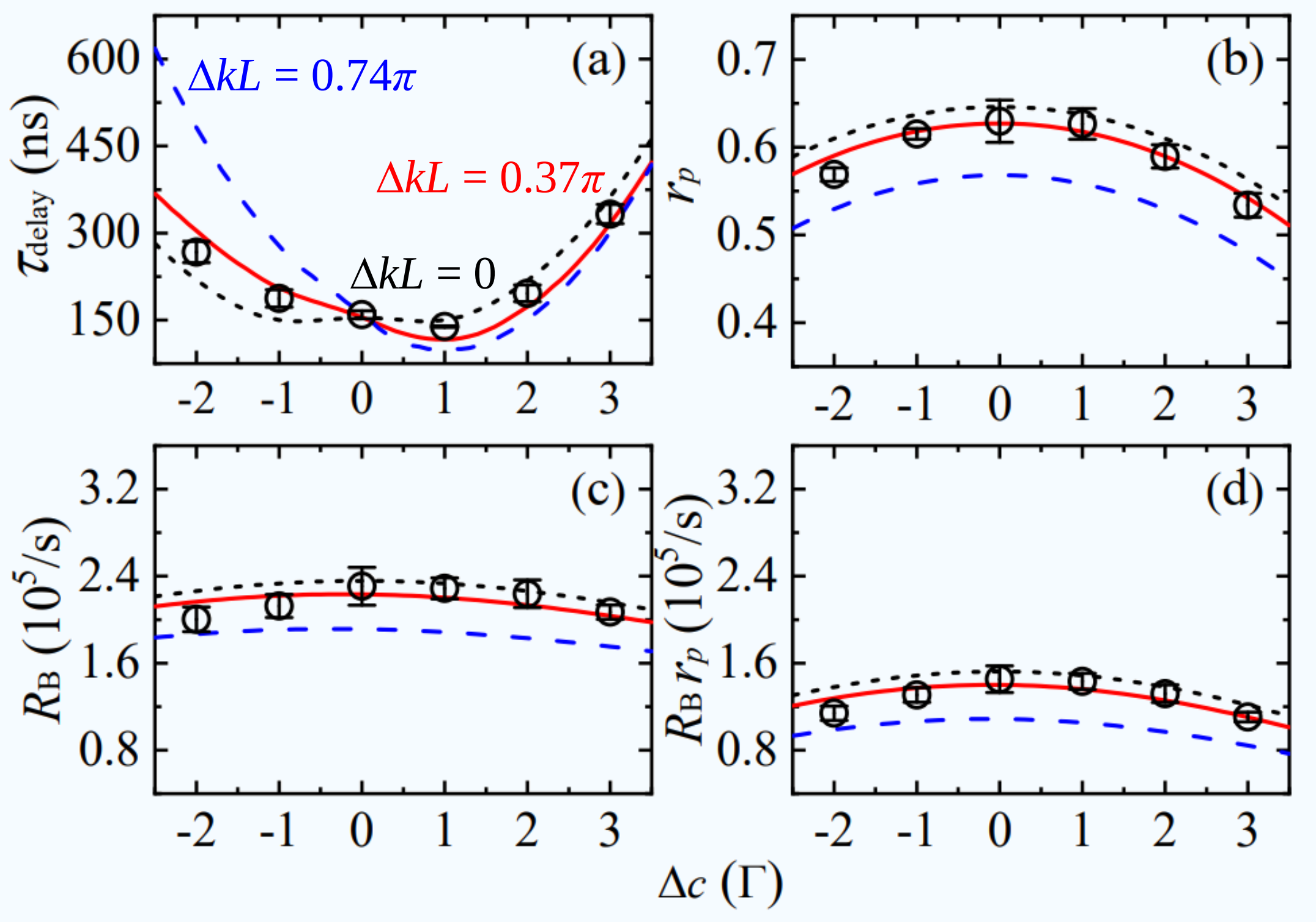


Fig. 3. Results of frequency-tunable biphotons with Ω_c = 1Γ. Parameters: Ω_c = 1Γ, OD = 10, Ω_d = 1Γ, Δ_d = 10Γ. (a) The delay time versus Δ_c. (b) The pairing ratio r_p versus Δ_c. (c) The biphoton generation rate R_B versus Δ_c. (d) The generation rate temporally correlated photons R_B r_p versus Δ_c.

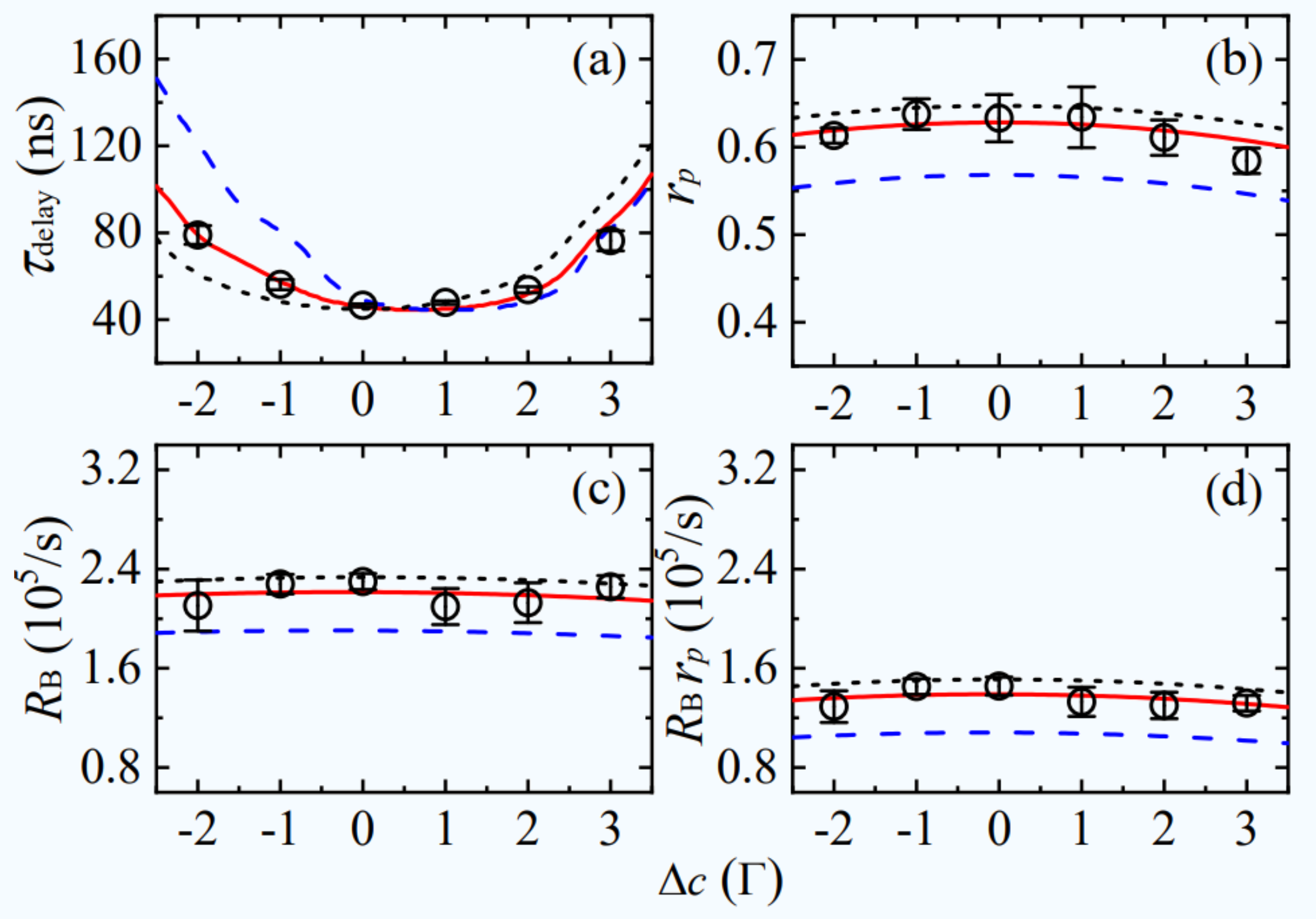


Fig. 4. Results of frequency-tunable biphotons with Ω_c = 2Γ. Parameters: Ω_c = 1Γ, OD = 10, Ω_d = 1Γ, Δ_d = 10Γ. (a) The delay time versus Δ_c. (b) The pairing ratio r_p versus Δ_c. (c) The biphoton generation rate R_B versus Δ_c. (d) The generation rate temporally correlated photons R_B r_p versus Δ_c.

Highly Correlated Ultrabright Biphotons

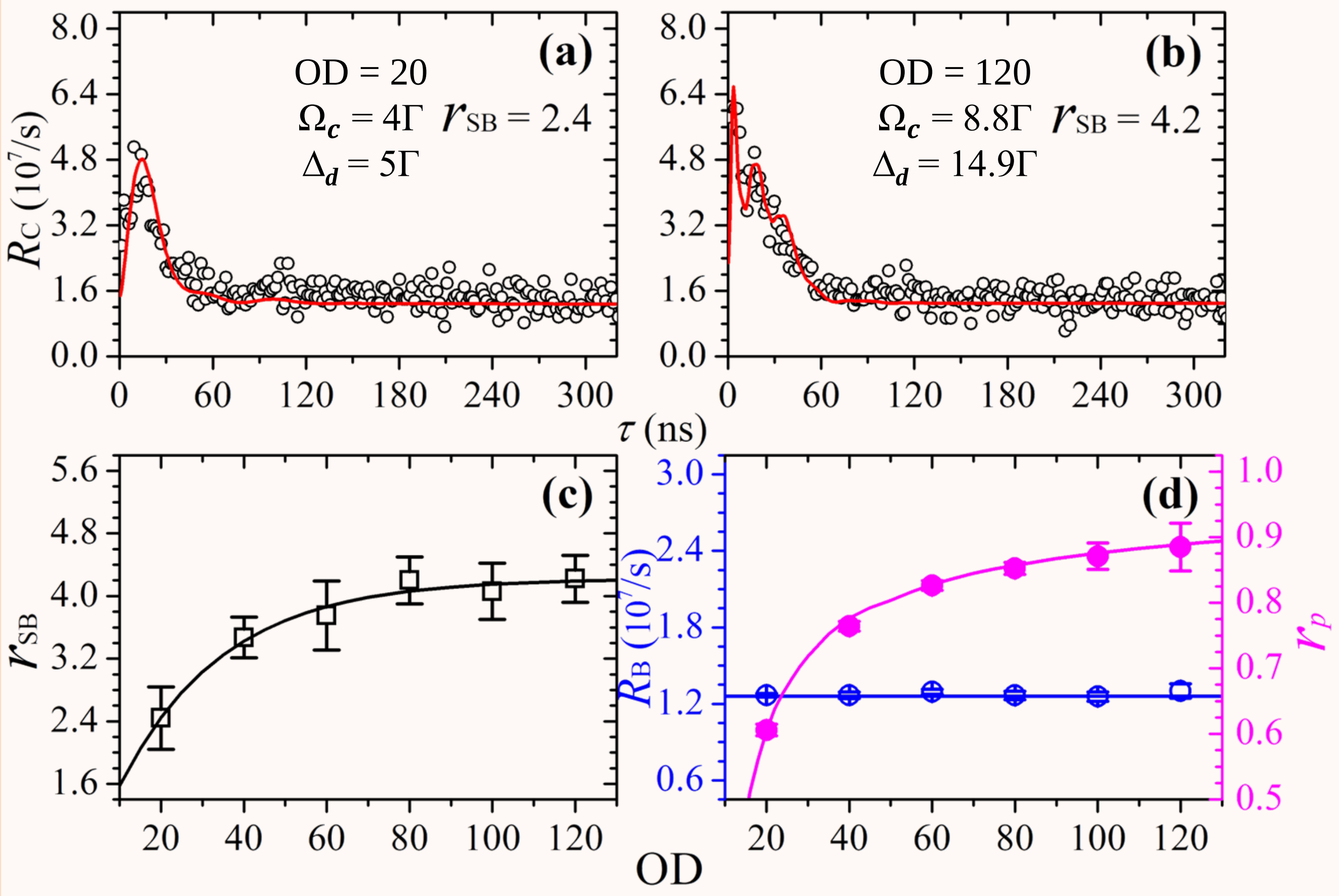


FIG. 6. Highly correlated ultrabright biphotons. Parameters: Ω_d = 3Γ, (a) OD = 20, Ω_c = 4Γ, Δ_d = 5Γ, and (b) OD = 120, Ω_c = 8.8Γ, Δ_d = 14.9Γ. (c) The peak signal-to-background ratio r_{SB} versus OD. (d) The biphoton generation rate R_B and pairing ratio r_p as a function of OD.

Conclusion

Our investigation into the biphoton pairing ratio, utilizing the double-Λ SFWM in cold ^{87}Rb atoms, revealed a marginal decrease at higher biphoton generation rates. However, this trend can be effectively addressed by elevating the atomic ensemble density. The highest pairing ratio observed was 0.89 at an OD of 120, accompanied by an ultrabright biphoton generation rate of up to 1.3 × 10^7 per second, surpassing previously reported rates in double-Λ SFWM studies. Furthermore, our experiment demonstrated the highest signal-to-background ratio of the biphoton wavepacket at 241, achieved at a low biphoton generation rate of 5.0 × 10^4 per second. This outstanding performance exceeded the Cauchy—Schwarz criterion by approximately 1.5 × 10^4 times. These results underscore the capability of the double-Λ SFWM scheme in advancing biphoton sources for future quantum technologies.

References

1. P. Kolchin, "*Electromagnetically-induced-transparency-based paired photon generation*," Phys. Rev. A **75**, 033814 (2007).
2. J.-S. Shiu et al., "*Observation of Highly Correlated Ultrabright Biphotons Through Increased Atomic Ensemble Density in Spontaneous Four-Wave Mixing*," arXiv : 2312.12758 (2023).
3. J.-S. Shiu et al., "*Frequency-tunable biphoton generation in spontaneous four-wave mixing*," submitted to Phys. Rev. A (2024).