

Perspective

Beyond Brightness: Biphoton-State Engineering with Nonlinear Metasurfaces

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Abstract: Nonlinear metasurfaces have been demonstrated as ultrathin photon-pair sources, bringing resonant nanophotonics into a field traditionally dominated by bulk crystals and waveguides. Early experiments established spontaneous parametric down-conversion from nanoantennas and metasurfaces and showed resonant enhancement. Recent experiments and theoretical proposals address a more specific objective: a metasurface that emits the biphoton state required by a particular quantum-optical experiment. Resonant dispersion, mode symmetry, quasi-bound states in the continuum, guided-mode resonances, flatband design, multi-resonance interference, polarisation engineering and tunable emission geometry can shape both the pair-generation probability and the spatial, spectral and polarisation structure of the emitted state. This Perspective examines how these physical parameters determine the joint amplitude and which measurements establish the resulting two-photon state.

Keywords: nonlinear metasurfaces; spontaneous parametric down-conversion; biphoton state; quantum light; spatial entanglement; quantum imaging

1. Introduction: Why Brightness Alone Is Insufficient

Patterning on the wavelength scale allows an optically thin element to control phase, polarisation, dispersion and radiation channels. In quantum photonics, the Nature Photonics review Metasurfaces for Quantum Photonics set out the broader context for quantum metasurfaces [1]. Related reviews, book chapters and perspectives cover quantum nonlinear metasurfaces, flat-optics quantum sources, quantum metaphotonics, nonlinear meta-optics enabled by bound states in the continuum (BICs) and nonlinear dielectric nanoresonators [2–6]. This article has a narrower aim: it focuses on metasurfaces in which resonant dispersion, symmetry and radiation-channel engineering directly shape the emitted two-photon state.

The first milestone was the direct observation of photon-pair generation in nanostructures. A single resonant AlGaAs nanoantenna generated photon pairs by spontaneous parametric down-conversion (SPDC), establishing that a nanoscale resonator could act as a quantum nonlinear source [7]. Resonant lithium-niobate metasurfaces then showed that an ultrathin patterned source could generate and spectrally tailor photon pairs [8]. Subsequent work demonstrated bidirectional emission from a resonant metasurface [9]. Together, these experiments established nanoscale pair generation, resonant spectral shaping and directional control.

A total pair rate does not show how many pairs enter the modes used by an experiment. Spectral or angular mismatch with imaging optics, fibres or detectors can make the collected rate much lower than the generated rate. Metasurface resonances and radiation channels can shape the spectrum, angular distribution and correlations at the source. Recent studies therefore treat the spatial, spectral and polarisation structure of the emitted state as quantities to be controlled at the source. Brightness remains essential, while mode matching and state properties determine how much of the emission can be used by a given experiment. This development is summarised in Figure 1.



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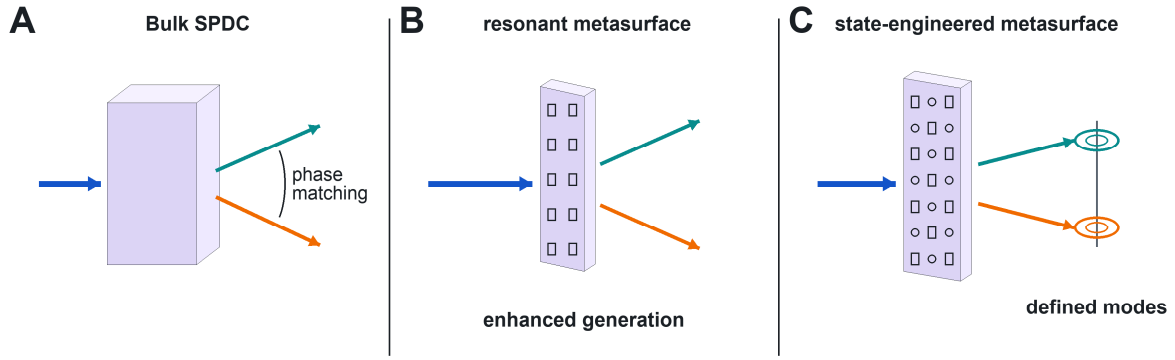


Figure 1. From source demonstration to biphoton-state engineering. (A) In a conventional bulk SPDC source, crystal length, phase matching, pump geometry and collection conditions jointly determine the emission geometry and correlations; (B) Early nonlinear metasurface sources established that ultrathin resonant structures can generate and enhance photon pairs; (C) In a state-engineered source, the metasurface acts as both the nonlinear medium and an optical antenna, shaping the angular, spectral and polarisation structure of the emitted biphoton state and directing photon pairs into defined modes.

2. What Makes Nonlinear Metasurfaces Different as Quantum Sources?

Bulk SPDC sources rely on propagation through a nonlinear crystal, where the pump field and longitudinal phase-matching function largely determine the joint spectrum and angular correlations. A nonlinear metasurface is short in the propagation direction but rich in transverse structure. Its resonances, reciprocal-lattice momentum, angular dispersion, mode symmetry and radiation channels determine how pump photons are converted and how signal and idler photons leave the device.

A metasurface can serve as both the nonlinear medium and an optical antenna. It can enhance fields at the pump, signal or idler wavelengths, direct radiation into selected angular channels, and introduce nonlocal guided-mode resonances with strong transverse dispersion.

The short propagation length relaxes longitudinal phase-matching constraints, so resonant modes, leakage channels and the finite transverse aperture become more important. A small change in unit-cell symmetry can open or suppress a radiation channel, a metagrating period can supply reciprocal-lattice momentum, and the pump waist or angle can select a different distribution of in-plane wavevectors. These familiar nanophotonic variables therefore shape the modal coefficients of the two-photon state.

Together, these features give metasurfaces a distinct source geometry. Bulk crystals offer mature phase matching and broad control through crystal length, pump shaping, poling and interferometric arrangements, while external optics often define the collected transverse modes. Waveguides combine long interaction lengths with strong confinement and natural collection into guided modes, although their output is tied to the available waveguide modes and couplers. Microresonators provide strong enhancement, narrow linewidths and direct frequency-mode control, with constraints from coupling and thermal locking. Metasurfaces provide direct access to transverse momentum, symmetry and free-space radiation channels within one patterned element. The metasurface experiments considered here use varied rate and collection conventions and generally do not report source-to-mode efficiency in comparable terms, which complicates direct comparison.

This geometry also imposes limitations. The short interaction length makes resonant enhancement important. A practical source requires coupling to selected input and output channels rather than large total radiative leakage. Resonant devices can be sensitive to fabrication and thermal detuning, and their collection efficiency depends strongly on the angular mode.

A convenient low-gain mode expansion of the emitted state is [2]:

$$|\Psi_{out}\rangle \simeq |0\rangle + \varepsilon|\psi_2\rangle,$$

$$|\psi_2\rangle = \sum_{\mu,\nu} c_{\mu\nu} \hat{a}_{s,\mu}^\dagger \hat{a}_{i,\nu}^\dagger |0\rangle, \quad \sum_{\mu,\nu} |c_{\mu\nu}|^2 = 1.$$

Here $|0\rangle$ is the vacuum and ε is the low-gain pair-generation amplitude. The operators $\hat{a}_{s,\mu}^\dagger$ and $\hat{a}_{i,\nu}^\dagger$ create signal and idler photons in outgoing modes μ and ν . These labels may include frequency, transverse momentum or collection mode, polarisation and radiation channel; the sums represent discrete sums or continuous integrals as appropriate. The normalised complex coefficients $c_{\mu\nu}$ specify the biphoton state in the chosen basis through their support, relative magnitudes and basis-dependent phases. Because the expansion retains only the leading pair amplitude, it omits the small normalisation correction to the vacuum term and all higher-pair terms. For the specified excitation and mode

normalisation, $|\varepsilon|^2$ gives the leading pair probability; a measured rate also depends on repetition rate or acquisition time, collection and detection. Indistinguishable signal and idler amplitudes require symmetrisation, while unresolved loss, background or environmental channels generally require a density operator.

Here, biphoton-state engineering means source-level control of the support, relative magnitudes or phases of the normalised two-photon component in a specified output-mode basis. Brightness enhancement changes the pair probability, usually through ε , without necessarily changing these coefficients. Selective resonant weighting of a generation channel therefore counts as source control when it changes the relative $c_{\mu\nu}$, even if it also changes ε . A design change can affect both quantities. Downstream filtering and post-selection instead select a conditional measured state, often reducing rate or heralding efficiency. In a metasurface, ε and the coefficients are shaped by the nonlinear tensor, pump field, resonant modes, Green functions, loss, finite aperture and radiation continua [2].

Stimulated-emission tomography (SET) can infer selected biphoton-state properties in the low-gain regime when the stimulated and spontaneous processes address the same modes, frequencies, polarisations and bandwidths [2,10]. Reciprocal nonlinear measurements additionally require the relevant reciprocity relation. Rozema et al. reconstructed a polarisation density matrix and predicted purity and concurrence using stimulated emission and classical detectors [11]. An intensity map in a single mode basis gives the squared magnitudes of the corresponding modal amplitudes, not their relative phases; phase recovery requires measurements in suitable coherent superpositions, a source model or an interferometric reference. Stimulated measurements do not directly observe spontaneous nonclassical correlations, and they do not determine spontaneous multipair probabilities, background statistics or heralding efficiency. Faruque et al. demonstrated quantum-referenced spontaneous-emission tomography for an integrated microring pair source, rather than a metasurface, by interfering its spontaneous emission with a reference pair source [12]. Classical and stimulated probes can therefore reveal important modal properties, while phase-sensitive or direct quantum measurements supply the information they do not contain.

3. Recent Progress in Biphoton-State Control

Theoretical studies predicted that multiple BIC-related resonances could enhance nondegenerate generation and tune polarisation entanglement, while metagrating dispersion could enhance angle-correlated emission and shape its angular spectrum [13,14].

Experiments with high-Q semiconductor metasurfaces extended this control to frequency and polarisation. GaAs quasi-bound-state-in-the-continuum (qBIC) structures produced resonantly enhanced nondegenerate entangled pairs and frequency-multiplexed states with possible relevance to frequency-bin and cluster-state schemes [15]. Subsequent work linked qBIC radiation properties and meta-atom symmetry to mixed or nearly pure reduced single-photon polarisation states in frequency-nondegenerate biphotons [16]. Overlapping qBIC and Mie pathways also produced Fano-like two-photon interference after polarisation analysis erased pathway information that would otherwise prevent coherent interference between the alternatives [17]. Taken together, these experiments show that resonance and symmetry engineering can define and weight multiple generation pathways at the source. In the Fano-interference experiment, observing the interference also required downstream polarisation projection to erase pathway distinguishability.

Lithium-niobate nonlocal metasurfaces generated spatially entangled pairs with resonant enhancement and high coincidence-to-accidental ratio (CAR) [18]. Their nonlocal guided-mode resonances link the transverse momenta of the generated photons to their far-field emission. A related theoretical analysis predicted control of spatial entanglement through pump wavelength and beam size, including the Schmidt number, which measures effective spatial-mode dimensionality [19]. Multiplexed metagratings then shaped the measured two-photon polarisation state through grating orientation [20].

Polarisation states have been controlled through several physical mechanisms. Nonlinear-symmetry breaking in InGaP nanoresonators enabled pump-wavelength tuning from partially entangled states towards a Bell state [21]. A plasmonic metasurface strongly coupled to an epsilon-near-zero material generated a polarisation-entangled Bell state by engineering anisotropy in the effective nonlinear response [22]. For this platform, the detected rate, loss and filtering conditions remain important alongside the Bell-state fidelity.

Guided-mode-resonance metasurfaces have demonstrated pump-wavelength tuning of co- and counterpropagating pair emission [23]. The pump selects signal and idler modes satisfying the transverse momentum conditions, thereby changing the joint angular distribution of the pairs. Quantum imaging experiments using metasurface-generated spatially entangled pairs exploited this link between source correlations, emission geometry and collection optics [24]. A later phase-gradient imaging experiment combined a LiNbO₃ pair-generating metasurface

with a silicon metasurface for phase-gradient extraction, so that metasurfaces supplied both the nonlinear source and the optical processor [25].

Theoretical designs and new materials broaden the range of accessible states. Dual-qBIC theory predicts enhanced generation concentrated near the surface normal [26], while guided-mode-cavity theory predicts pump-wavelength control of the emission direction [27]. Flatband designs have been proposed for broad, more uniform angular emission, including a numerical InGaP implementation based on tailored multipolar resonances [28,29]. Experiments have also demonstrated SPDC in a 3R-MoS₂ qBIC metasurface [30]. As an adjacent third-order example, amorphous-silicon metasurfaces show how Mie resonances, Raman background and photothermal detuning reshape spontaneous four-wave mixing (SFWM) pair generation [31].

Representative experimental conditions and outcomes are summarised in Table 1.

Table 1. Representative experimental metasurface SPDC sources. Values follow the authors' definitions. Rates are detected unless labelled inferred. Pump format, collection, filtering, timing and loss corrections differ, so no cross-platform ranking is implied. Theoretical quantities are identified and unreported quantities are not estimated. Comparable source-to-mode heralding efficiencies and experimentally extracted Schmidt numbers were not reported. CAR, coincidence-to-accidental ratio; NA, numerical aperture; CW, continuous-wave; FWHM, full width at half maximum; $g_{si}^{(2)}(0)$, signal-idler second-order cross-correlation at zero delay.

Source and Controlled Property	Pump and Collection	Rate or Enhancement	State or Correlation Result
LiNbO₃ resonant metasurface [8] Resonant spectral tailoring; backward emission.	788 nm CW; approximately 70 mW; 6 µm beam diameter. Reflection, NA 0.14; 50 nm filter at 1575 nm.	5.4 Hz detected at approximately 70 mW; spectral-density enhancement up to 130-fold at resonance and approximately 20-fold over 50 nm.	CAR up to 361; detected rate includes collection and detector losses.
LiNbO₃ nonlocal metagrating [18] Spatial antibunching and multimode entanglement.	CW near 785 nm; 85 mW; approximately 100 µm beam diameter. Multimode-fibre collection over approximately 0.7°; 50 nm filter.	1.8 Hz detected at 85 mW; 2.3–3.5 Hz/mW inferred within the calibrated angle; 450-fold enhancement.	CAR approximately 5000; spatial antibunching violated a Cauchy-Schwarz inequality. Predicted SPDC bandwidth approximately 3 nm; inferred rate uses estimated efficiencies.
GaAs qBIC metasurfaces [15] Nondegenerate and frequency-multiplexed states.	CW near 725 nm; one detuning scan used 725.4 nm and 9.6 mW. Fibre-coupled spectroscopy; conditions varied.	No single benchmark rate; coincidences reported versus detuning.	$g_{si}^{(2)}(0) = 10.5 \pm 1.1$; Cauchy-Schwarz violation above 50 standard deviations. Multifrequency emission was demonstrated; coherent cluster-state generation was proposed.
GaAs qBIC-Mie metasurfaces [17] Fano-like interference between generation pathways.	790.8 nm CW; 55 mW; approximately 200 µm FWHM beam diameter. Single-mode-fibre collection; effective NA approximately 0.14.	0.69 ± 0.03 and 2.5 ± 0.1 Hz detected for two pathways; 7.6 ± 0.2 Hz in a second device.	Nonclassical cross-correlations and Fano-like two-photon interference after polarisation projection. Above-bandgap photoluminescence was present; pathway information was erased.
LiNbO₃ nonlocal metagrating [23] Tunable co- and counterpropagating emission.	785 nm CW; 91 mW; tuned over 782.7–789.5 nm. Forward and backward multimode-fibre collection.	At 91 mW: 1.28 ± 0.06 Hz copropagating; 2.92 ± 0.09 Hz counterpropagating.	CAR up to 7500 for counterpropagating pairs; fibre coupling varied with angle; heralding efficiency was not extracted.
InGaP(110) resonant metasurface [21] Tunable polarisation entanglement.	CW, 778–787 nm. Counterpropagating arms; 3° collection; 50 nm filters; 0.486 ns coincidence window.	0.1 Hz/mW detected; 25-fold enhancement over unpatterned film.	At 779 nm: fidelity 0.95, concurrence 0.9. Across tuning: concurrence approximately 0.9–0.7, purity above approximately 0.8; maximum CAR approximately 7×10^4 . Hyperentanglement extension was theoretical.
Au/indium-tin-oxide (ITO) epsilon-near-zero metasurface [22] Bell-state generation through anisotropic effective nonlinearity.	775 nm CW; 3 mW. NA 0.5 excitation and collection; fibre-coupled; 50 nm filter.	5.4×10^{-3} Hz/mW pump-normalised detected rate.	CAR 40; Bell-state fidelity 0.91. Rate includes propagation, filtering and detector losses.
LiNbO₃ nonlocal metagrating [24] Tunable angular emission used for optical-scanning and ghost imaging.	CW, 779–790 nm; 80 mW rate benchmark; 85 mW imaging. Angular scan/slit and fibre collection; emission 1558–1580 nm.	6 Hz detected at 80 mW (75 mHz/mW); 65-fold enhancement.	$g_{si}^{(2)}(0)$ approximately 7000 (authors used generic notation); spatial anticorrelation and imaging contrast. One-hour acquisitions; wider field of view and resolution were modelled.

4. Metasurface Parameters and the Emitted State

Table 2 summarises how familiar nanophotonic parameters affect the emitted state and the quantities used to measure it. The same parameters can change selected modal coefficients and the overall pair probability.

Table 2. Influence of metasurface parameters on the emitted biphoton state.

Metasurface Parameter	Optical Effect	Effect on Emitted State	Measured Quantity
Resonant mode structure and loaded Q factor	Balances field build-up, spectral selectivity, radiative leakage and non-radiative loss.	Shapes pair probability, resonance-selected bandwidth, angular acceptance and useful outcoupling.	Rate into the target mode, linewidth, angular acceptance, outcoupling and stability.
Angular dispersion and lattice momentum	Maps wavelength and in-plane momentum to radiation angle and couples guided modes to free-space channels.	Shapes the joint angular spectrum and selects signal-idler directions, including co- and counterpropagating paths.	Joint angular spectrum, emission-angle range and rate within a defined numerical aperture.
Mode symmetry and coherent pathways	Sets pump coupling, nonlinear overlap, leakage channels and the relative amplitudes and phases of overlapping resonances.	Controls polarisation states, frequency multiplexing, pathway distinguishability and interference.	State tomography, joint spectrum and phase, and two-photon interference.
Pump field	Sets wavelength, bandwidth, polarisation, incidence angle, waist, wavefront and pulsed or continuous-wave format.	Selects in-plane momenta and can change both pair probability and the modal coefficients.	Correlation width, Schmidt number or mode spectrum, target-mode overlap and rate under stated excitation.
Nonlinear material platform	Provides nonlinear susceptibility, loss, dispersion, damage threshold and fabrication route.	Constrains rate, background, wavelength range and polarisation pathways.	Pair rate under stated excitation conditions and bandwidth, loss, background and pump-power handling.
Finite aperture, disorder and fabrication tolerance	Set momentum resolution and introduce resonance shifts, splitting, broadening or parasitic scattering.	Affect correlation width, parasitic-mode content, stability and device-to-device variation.	Angular or spectral repeatability, target-mode overlap and device-to-device spread.
Emission and outcoupling geometry	Defines transmission, reflection, copropagating, counterpropagating, fibre-coupled or waveguide-coupled outputs.	Determines whether the pair can be delivered to the next optical element.	Rate into a target mode, raw or Klyshko heralding efficiency, and a loss-corrected estimate of source-to-mode collection efficiency.
Tunability mechanism	Uses changes in pump conditions, geometry, electro-optic response, photothermal detuning or reconfigurable materials.	Addresses different states, angles or spectra while potentially changing rate, loss, noise or stability.	Tuning range, repeatability, CAR and state fidelity across tuning.

For resonant sources, Q is meaningful only together with channel-specific coupling. The resonance must provide field build-up while still coupling the pump into the structure and the signal and idler into the required output channels. Parasitic radiation and absorption reduce this balance. Increasing Q narrows the resonance-selected linewidth and, for a dispersive resonance, can reduce angular acceptance. It also increases sensitivity to pump-bandwidth mismatch, fabrication error and thermal detuning. The full biphoton bandwidth also depends on the pump spectrum, material dispersion, finite aperture and collection.

The transverse pattern provides further degrees of freedom. Angular dispersion and reciprocal-lattice momentum select radiating wavevectors, while mode symmetry and overlapping resonances set pathway amplitudes, phases and distinguishability. Pump wavelength, bandwidth, polarisation, incidence angle, waist and wavefront determine which modes are excited. Finite aperture broadens the momentum response, while disorder and fabrication error can shift, split or broaden the resonances [5,6].

Collection geometry matters directly. A high generated rate spread over an unsuitable numerical aperture may deliver fewer pairs than a lower-rate source matched to the required mode. Electro-optic, photothermal and reconfigurable-material tuning can change the emitted state, but their effects on loss, noise and stability must also be measured.

The relevant parameters depend on the experiment. Quantum imaging may require a broad, characterised joint angular spectrum, whereas Bell-state generation requires balanced coherent decay amplitudes and low pathway distinguishability. Fibre or waveguide collection places the emphasis on pair rate into a specified spatial mode. Each case calls for different resonances, symmetries, pump conditions and measurements.

These parameters are coupled. A broad, correlated angular response can support a large spatial-mode dimensionality while complicating collection into a small number of modes. A material with a large nonlinear response may also introduce absorption or background noise. Yao et al. recently combined local Mie and nonlocal qBIC resonances in a classical nonlinear meta-lens to balance conversion efficiency, wavefront phase and directional asymmetry [32]. Although the experiment concerned harmonic generation rather than photon pairs, it shows how the resonance structure can control several optical quantities at once. A separate numerical study combined quantum and classical calculations to optimise Bell-state fidelity and collected SPDC rate for an AlGaAs

metasurface, predicting a fidelity of 0.989 and a collected rate of 55 Hz/mW [33]. Figure 2 illustrates how the required biphoton state determines the relevant metasurface parameters and measurements in two cases.

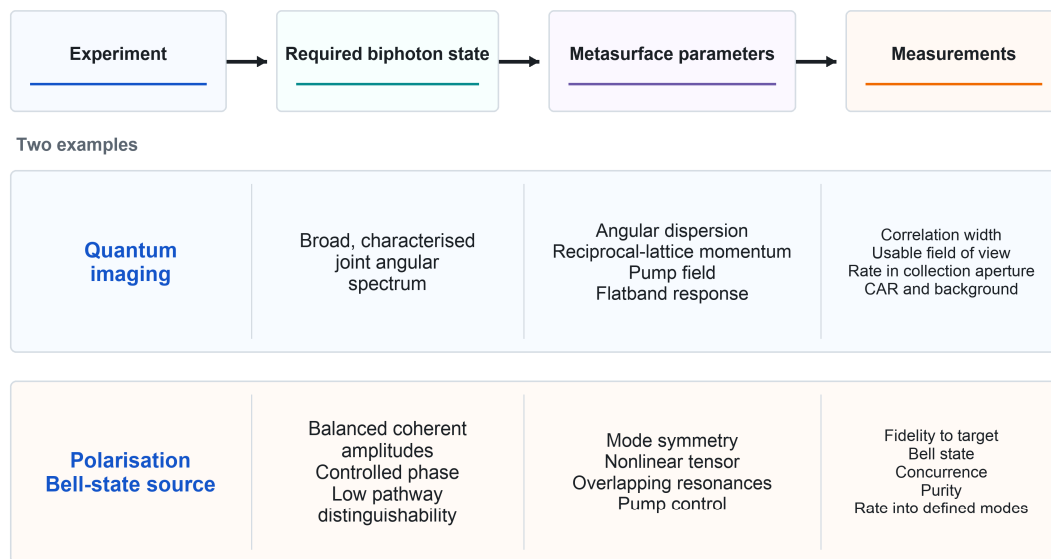


Figure 2. Two examples relating a required biphoton state to metasurface parameters and measurements. For quantum imaging, a broad, characterised joint angular spectrum can be shaped through angular dispersion, reciprocal-lattice momentum, the pump field and a flatband response. Relevant measurements include correlation width, usable field of view, rate within the collection aperture and coincidence-to-accidental ratio (CAR) or background counts. A polarisation Bell-state source requires balanced coherent decay amplitudes, a controlled relative phase and low pathway distinguishability. Mode symmetry, the nonlinear susceptibility tensor, overlapping resonances and pump settings can determine these properties. Fidelity measures overlap with the target Bell state; for the two-qubit polarisation state, concurrence quantifies entanglement. Purity and rate into defined modes provide complementary information. The two examples do not imply a universal mapping between parameters and measurements.

5. Assessing the Generated Photon Pairs

Brightness remains important, but a reported value is meaningful only when its excitation, bandwidth and collection conditions are specified. Enhancement over an unpatterned film shows the effect of patterning under the reported conditions; it does not establish how many pairs enter the mode used by the experiment.

The modal expansion in Section 2 distinguishes rate-related quantities from properties of the normalised two-photon state. Pair probability and detected rate describe how often pairs are generated and observed, while heralding efficiency describes conditional delivery or detection. Fidelity, purity, interference visibility and Schmidt number characterise the state itself.

For nonlinear quantum metasurfaces, generated, collected, detected and usable rates can differ substantially because the angular emission is structured. Relevant context includes pump format and power, spectral and angular collection windows, filtering, coincidence window, and background or accidental counts. For pulsed excitation, pair probability per pulse should be distinguished from average detected rate. Raw heralding efficiency, often reported as a Klyshko efficiency, is a conditional detection probability that includes transmission and detector losses; calibrated losses can be used to estimate delivery into the selected mode. When heralded single-photon operation is claimed, the heralded second-order correlation $g_h^{(2)}(0)$ is also informative. For collection into an optical system, the rate in a defined free-space, fibre or waveguide mode is particularly relevant. Coincidence-to-accidental ratio (CAR) compares signal-idler coincidences with an estimate of accidentals, but its calculation differs among experiments. The convention and coincidence window should therefore accompany the value.

State metrics answer different questions. Fidelity quantifies overlap with a stated target state, while purity quantifies mixedness of the reconstructed density operator. Both depend on the reconstructed subspace and the treatment of background and loss. For a pure bipartite state, the Schmidt number characterises effective modal dimensionality. An intensity-only joint spectrum does not generally determine it when the joint phase is unknown. Hong-Ou-Mandel visibility probes indistinguishability in the interfering modes. Raw and background-corrected values should be distinguished, while multipair emission and mode mismatch remain separate physical limitations.

Tunability should be considered together with changes in rate, bandwidth, noise and state quality. In semiconductor platforms pumped above the bandgap, photoluminescence can be appreciable, as observed in the GaAs Fano-interference experiment [17]. Background and multipair events can then degrade CAR, measured fidelity and measured state purity.

The distinction from post-selection is clearest when the desired correlations are generated before filtering. Filtering is often necessary, but a target state recovered only after discarding most of the emission may carry a much lower collected rate than the source brightness suggests.

6. Outlook

Metasurfaces complement established bulk, waveguide and microresonator sources through direct free-space access, structured emission, angular dispersion and the possibility of combining generation with wavefront or mode shaping in one ultrathin element.

Current directions include quantum imaging, structured biphoton states, tunable sources, and interfaces between free-space and on-chip quantum optics. Recent phase-gradient imaging combined a nonlinear quantum source with a silicon metasurface for phase-gradient extraction [25]. Metasurfaces may be valuable where relaxed longitudinal momentum constraints, engineered transverse momentum or direct definition of a free-space mode are advantageous. Theoretical work on adjacent processes, including third-order spontaneous parametric down-conversion in resonant metasurfaces, extends the range of quantum states beyond biphoton generation [34].

Inverse nanophotonic design can target joint spectra, angular correlations, polarisation states, mode overlap and rate [33]. Sum-frequency generation and stimulated measurements can assist when their modal correspondence and phase limitations are respected [2,10–12]. Future studies could include source-to-mode heralding efficiency, pump-power dependence and fabrication tolerance among the quantities being optimised.

Further progress will require nonlinear overlap, resonant dispersion, loss and radiation channels to be considered together. Pair-generation probability should be assessed alongside the emitted correlations and collection geometry.

Author Contributions

A.S.S. conceived the article and wrote the manuscript. The author has read and agreed to the published version of the manuscript.

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The author declares no conflict of interest.

Use of AI and AI-Assisted Technologies

During the preparation of this work, the author used OpenAI Codex to improve the language and readability of the manuscript. The author reviewed and edited the content as needed and takes full responsibility for the content of the published article.

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