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uantum key distribution (QKD) is essential for secured information delivery, which can be facilitated via polarization,^{1,2} orbital angular momentum (OAM),^{3,4} or a combination of spin angular momentum (SAM) and OAM of photons.^{5–7} The SAM–OAM hybrid states consist of a SAM associated with circularly polarized states and an OAM associated with a helical phase, $e^{il\varphi}$, where l is the topological charge and φ is the azimuthal angle. They have been widely investigated in generating,^{8,9} transporting,^{10,11} and distributing⁵⁻⁷ quantum states with conventional optical setups for QKD. For example, a SAM-OAM hybrid state can encode and manipulate information simultaneously to boost photonic information processing capacity and enhance the noise resistance capability.^{6,12} In conventional generation, transportation, and detection of hybrid states, many waveplates and beam splitters are required to establish a single-channel twoparty communication.^{5,6} Recently, a point-to-multipoint QKD network configuration for multiuser communication has been built with conventional optical components to transform and distribute hybrid states.¹³ However, as the user number increases, the network demands more beam splitters, waveplates, wavelength division multiplexers, optical switches, etc., leading to significant electromagnetic loss and heavier, bulky optical platforms.^{14–16}

Unlike conventional optical devices, the metasurface provides optical multifunctions¹⁷⁻¹⁹ by controlling the phase, amplitude, SAM, and OAM of photons on a subwavelength

scale.^{20–22} So far, metasurfaces have been applied in generation of quantum entanglements²³⁻²⁷ and reconstruction of quantum states,^{28,29} quantum imaging,³⁰ and quantum interference.³¹ Recently, simultaneous entanglement distribution and transformation of different polarization states have been realized with metasurfaces based on the geometricalscaling-induced (GSI) phase.²⁷ However, metasurfaces have not yet been applied to the QKD to the best of our knowledge. In fact, the metasurface is particularly effective at replacing bulky and complicated combinations of conventional optical components for integrated point-to-multipoint QKD networks. Here, we demonstrate the first realization of multiprotocol QKD (mQKD) based on a multichannel silicon metasurface. When a photon of polarization-entangled photon pairs interacts with the metasurface, photonic spin-orbit conversion occurs and the topological charge and polarization are changed. Consequently, multiple SAM-OAM hybrid states can be achieved by elaborately designing the metasurface. As examples, we showcase that SAM-OAM hybrid states are applicable for proof-of-principle QKD protocols of both BB84

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Downloaded via NANJING UNIV on May 17, 2025 at 06:13:39 (UTC). See https://pubs.acs.org/sharingguidelines for options on how to legitimately share published articles. and BBM92 with a high secret key rate and a low quantum bit error rate. Other protocols, such as the E91 protocol, can also be incorporated into this metasurface.

The Principle of Metasurface-Based mQKD. To perform mQKD, we first generate biphoton SAM-OAM hybrid states by interacting the polarization-entangled photon pairs with a metasurface. As illustrated in Figure 1a, the polarization-entangled photon pairs are expressed as $|\psi^-\rangle_{12} = (|R\rangle_1|L\rangle_2 - |L\rangle_1|R\rangle_2)/\sqrt{2}$, where $|L\rangle$ and $|R\rangle$ represent left- and right-handed circularly polarized states and subscripts 1 and 2 denote the optical paths 1 and 2, respectively. The photons via path 1 interact with the metasurface, and photonic spin-orbit conversion occurs in one output channel, i.e.,



Figure 1. Schematics of generating different biphoton SAM-OAM hybrid states for mQKD. (a) One photon of polarization-entangled photon pair $|\psi^{-}\rangle_{12}$ interacts with the multichannel metasurface in path 1 and generates the output channels α_a , β_v , or γ_m . The photons from channels in path 1 and that in path 2 generate the hybrid states $|\Psi_{\alpha}^{q}\rangle_{12}$ $|\Psi_{\beta}^{p}\rangle_{12}$, or $|\Psi_{\gamma}^{m}\rangle_{12}$, respectively. (b) We implement the BB84 protocol with the state $|\Psi_{\alpha}^{q}\rangle_{12}$ $(|\Psi_{\beta}^{p}\rangle_{12})$ (blue and green) and BBM92 protocol with state $|\Psi_{\gamma}^{m}\rangle_{12}$ (red). With the BB84 protocol, photon pair $|\Psi_{\alpha}^{q}\rangle_{12}$ $(|\Psi_{\beta}^{p}\rangle_{12})$ output photons in channel $\alpha_{q}(\beta_{p})$ (path 1) and in path 2. In channel $\alpha_q(\bar{\beta}_p)$ (path 1), Alice^q (Alice^p) and Bob^q (Bob^p) prepare and measure the state of the photon with waveplates, polarization beam splitters (PBSs), and spatial light modulators (SLM), respectively. In path 2, the photon is heralding single photon. The photons are received by single-photon counting modules (SPCMs). The above process is recorded by a coincidence count. Meanwhile, with the BBM92 protocol, the photon pair $|\Psi_{\gamma}^{m}\rangle_{12}$ establishes the photon in channel γ_m (path 1) and path 2. After the photon in channel γ_m passes through PBS, $|\Psi_{\gamma}^{m}\rangle_{12}$ is transformed to the state $|\Psi_{\gamma}^{m}\rangle_{12}$. Alice^m and Bob^{*m*} make projective measurements to obtain the coincidence counts by waveplates, PBS, SLM, and SPCMs.

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where A_L and A_R are the amplitude of output circularly polarized components and OAM states $|l\rangle$ and $|l'\rangle$ associate with the azimuthal phase factor of $e^{il\varphi}$ and $e^{il'\varphi}$, respectively. Consequently, the incident state $|\psi^-\rangle_{12}$ is transformed to the output of SAM–OAM hybrid states as

$$|\psi\rangle_{12} = (A_L |l\rangle_1 |L\rangle_2 - A_R |l'\rangle_1 |R\rangle_2 / \sqrt{2}$$
(2)

We achieve multichannel outputs as (i) Q channels (α_q) with $A_L = 1$ and $A_R = 0$, i.e., $|\Psi_q^a\rangle_{12} = |l_q^a\rangle_1|L\rangle_1|L\rangle_2$; (ii) P channels (β_p) with $A_L = 0$ and $A_R = 1$, i.e., $|\Psi_p^p\rangle_{12} = |l_p^p\rangle_1|R\rangle_1|R\rangle_2$; (iii) M channels (γ_m) with $A_L = A_R$, i.e., $|\Psi_\gamma^m\rangle_{12} = (|l_\gamma^m\rangle_1|L\rangle_1|L\rangle_2 - |l_{\gamma}^{'m}\rangle_1|R\rangle_1|R\rangle_2)/\sqrt{2}$. These SAM–OAM hybrid states can be employed in mQKD.

As an example, we can perform the BB84 protocol³² with $|\Psi_{\alpha}^{q}\rangle_{12}$ and $|\Psi_{\beta}^{p}\rangle_{12}$ generated from the metasurface. As illustrated in the blue flowchart of Figure 1b, the photon pairs with state $|\Psi_{\alpha}^{q}\rangle_{12}$ are distributed to channel α_{α} (path 1) and path 2. In path 1, Alice^q converts the state $|\hat{l}_{\alpha}^{q}\rangle_{1}|L\rangle_{1}$ in channel α_a to one basis state of mutually unbiased bases (MUBs) $\{|\kappa_i\rangle_1^A\}$ and $\{|\mu_i\rangle_1^A\}$ with waveplates, where i = 1, 2, i.e., i.e. $|\kappa_1\rangle = |l_{\alpha}^q\rangle|H\rangle, \ |\kappa_2\rangle = |l_{\alpha}^q\rangle|V\rangle, \ |\mu_1\rangle = |l_{\alpha}^q\rangle|D\rangle, \ \text{and} \ |\mu_2\rangle = |l_{\alpha}^q\rangle|A\rangle.$ Here $|H\rangle$, $|V\rangle$, $|D\rangle$, and $|A\rangle$ represent horizontal, vertical, diagonal, and antidiagonal polarized states. These basis states have a doughnut shaped intensity distribution and contain only linearly polarized states (Figure 1b). While Bob^q measures photon with the MUBs $\{|\kappa_i\rangle_1^B\}$ and $\{|\mu_i\rangle_1^B\}$ in path 1 with waveplates, polarization beam splitters (PBS) and spatial light modulator (SLM) project the heralding single photon in path 2 onto state $|L\rangle_2$ to declare that the output photon in channel α_a experiences the process of preparation and measurement, as recorded by coincidence count. In this way, we verify the BB84 protocol with the state $|\Psi_{\alpha}^{q}\rangle_{12}$. Similarly, the state $|\Psi_{\beta}^{p}\rangle_{12}$ can be introduced to the BB84 protocol with similar processes (green flowchart in Figure 1b).

We can also carry out the BBM92 protocol³³ with state $|\Psi_{\gamma}^{m}\rangle_{12}$ with the same metasurface. In the red flowchart of Figure 1b, by projecting the photon in the channel γ_m onto $|H\rangle_1$ via PBS, the state $|\Psi_{\gamma}^m\rangle_{12}$ is transformed to an entangled state $|\Psi_{\gamma}^{\prime m}\rangle_{12} = (|l_{\gamma}^{m}\rangle_{1}|L\rangle_{2} - |l_{\gamma}^{\prime m}\rangle_{1}|R\rangle_{2})/\sqrt{2}$, shared by Alice^m and Bob^m. Suppose Alice^m selects MUBs $\{|L\rangle_2, |R\rangle_2\}$, $\{|H\rangle_2,$ $|V\rangle_2$ by waveplates and PBS and Bob^m selects MUBs $\{|l_{\gamma}^m\rangle_1$ $|l'_{\gamma}^{m}\rangle_{1}$, $\{|d_{ll'}^{m}\rangle_{1}, |a_{ll'}^{m}\rangle_{1}\}$ by SLM to make projective measurements to obtain the coincidence counts, where $|l_{\gamma}^{m}\rangle_{1}$ and $|l_{\gamma}^{m}\rangle_{1}$ are single OAM states, and $|d_{l,l'}^m\rangle_1$ and $|a_{l,l'}^m\rangle_1$ are OAM superposition states with $|d_{l,l'}^m\rangle = (|l_{\gamma}^m\rangle_1 + |l_{\gamma'}^m\rangle_1)/\sqrt{2}$, and $|a_{l,l'}^m\rangle = (|l_{\gamma}^m\rangle_1 - |l_{\gamma}'^m\rangle_1)/\sqrt{2}$. It follows that the basis states of Alice's MUBs have the Gaussian intensity distribution with uniform polarization, while Bob's MUBs possess donut-shaped or multiple-lobe intensity distribution with horizontal polarization. In this way, a proof-of-principle BBM92 protocol with state $|\Psi_{\gamma}^{m}
angle_{12}$ is attested. Similarly, the modified E91 protocol³⁴ can also be implemented with state $|\Psi_{\gamma}^{m}\rangle_{12}$ with the same metasurface.

Design, Fabrication, and Characterization of Metasurface. We design the metasurface consisting of nanopillars to realize the multichannel transformation of SAM and OAM.



Figure 2. Experimental characterization of the fabricated metasurface. (a) Scanning electron micrographs of the metasurface. The scale bars represent 800 nm. (b) The simulated (blue) and the measured (red) transmittance of output beams in different channels. (c) The measured total intensity patterns (column 1) and the intensity patterns per channel of horizontally, vertically, right-handed circularly, left-handed circularly, diagonally, and antidiagonally polarized components (columns 2-7). The measured interference patterns (columns 8-9).

The rotation angle distribution $\theta(x, y)$ of the nanopillars in the dielectric metasurface satisfies^{35–37}

$$2\theta(x, y) = \arg\left(\sum_{a=1}^{n} A_{a} e^{i(l_{a}\varphi + (2\pi/\lambda)\sin\theta_{x}^{a}x + (2\pi/\lambda)\sin\theta_{y}^{a}y)}\right)$$
(3)

where the subscript *a* denotes the *a*th output, A_a represents the amplitude, l_a is the topological charge, λ is the wavelength, and θ_x^a (θ_y^a) is the diffraction angle. Based on eq 3, we design a metasurface consisting of four output channels (i, ii, iii, iv), with diffractive angles (θ_x^a, θ_y^a) as (0°, 5°), (0°, -5°), (-5°, 0°), and (5°, 0°), respectively.³⁸ When the horizontally polarized beam inputs on the metasurface, the output beams of channels i, ii, iii, and iv have a donut-shaped intensity distribution with zero intensity at the center, and the circularly polarized components of output beams have spiral phase distributions.

Our fabricated metasurface consists of identical silicon nanopillars with different rotation angles (Figure 2a) within an area of 258 × 258 μ m² and is made by electron beam lithography followed by dry etching.³⁸ The transmittance $I_{out, w}/I_{in}$ of channels (i, ii, iii, iv) is measured by a power meter with input horizontally polarized beams with wavelength 813 nm,³⁸ where $I_{out, w}$ is the output intensity in channel w (w = i, ii, iii, iv) and I_{in} is the incident intensity. As shown in Figure 2b, the transmittance of the four channels (i–iv) is in good agreement with simulations, where the deviation arises from fabrication errors.

To characterize the metasurface, we first set up a classical optical system to measure the electric field intensity and phase distributions of the beams in channels (i, ii, iii, iv).³⁸ The

intensity patterns (columns 1-7, Figure 2c) with horizontally polarized input beams and the interference patterns (columns 8-9, Figure 2c) of output beams per channel and Gaussian beams are recorded by a camera. Figure 2c indicates that the main components of output beams in channels i and ii are $|+1\rangle|L\rangle$ and $|-1\rangle|R\rangle$. The output beams from channels iii and iv possess the identical state $(|+1\rangle|L\rangle + |-1\rangle|R\rangle)/\sqrt{2}$. The experimental results are in good agreement with simulations.³⁸ Therefore, the metasurface indeed converts the input state to different output states in different channels. Then, we characterize the multichannel metasurface with a single-photon incidence of 810 nm. With our fabricated sample, the fidelities⁴⁹ of single-photon hybrid states reach 0.8985, 0.9045, 0.9754, and 0.9721, respectively.³⁸ This indicates that the metasurface can generate multiple biphoton SAM-OAM hybrid states for QKD protocols.

Generation and Characterization of Biphoton SAM– OAM Hybrid States. Now, we utilize the setup (Figure S6) to generate biphoton SAM–OAM hybrid states $|\Psi^q\rangle_{12}$ (q = 1, 2, 3, 4), i.e., $|\Psi^1\rangle_{12} = |+1\rangle_1 |L\rangle_1 |L\rangle_2$, $|\Psi^2\rangle_{12} = |-1\rangle_1 |R\rangle_1 |R\rangle_2$, and $|\Psi^3\rangle_{12} = |\Psi^4\rangle_{12} = (|+1\rangle_1 |L\rangle_1 |L\rangle_2 - |-1\rangle_1 |R\rangle_1 |R\rangle_2 / \sqrt{2}$, for BB84 and BBM92 protocols. As shown in Figure S6, the entangled state $|\Psi^-\rangle_{12}$ is generated by the Sagnac ring and waveplates. The photons in path 1 are spatially diffracted to four channels after they interact with the metasurface. We analyze SAM and OAM of the output states from channel w (w= i, ii, iii, iv) (path 1) and path 2 to obtain coincidence counts between two single-photon counting modules. The quantum state tomography (QST) and maximum likelihood estimation (MLE)⁵⁰ are employed to reconstruct the density matrix ρ_q (q = 1, 2, 3, 4) of state $|\Psi^q\rangle_{12}$ (q = 1, 2, 3, 4) (Figure 3), achieving the fidelities 0.8520, 0.8644, 0.9326, and 0.9411, respectively.³⁸ The results confirm the generation of four SAM–OAM hybrid states $|\Psi^q\rangle_{12}$ (q = 1, 2, 3, 4). The nonunity fidelity shows that the generated state deviates from the ideal one, which may result from the errors in sample fabrication and the inaccuracy in operating waveplates.

BB84 Protocol. We can apply the hybrid states $|\Psi^q\rangle_{12}$ (q = 1, 2, 3, 4) to perform the metasurface-based mQKD. First, we take metasurface-generated hybrid states $|\Psi^1\rangle_{12}~(|\Psi^2\rangle_{12})$ to perform the proof-of-principle BB84 protocol (Figure 1b). The photon pair with state $|\Psi^1\rangle_{12}$ $(|\Psi^2\rangle_{12})$ outputs photon with state $|\Phi^1\rangle_1 = |+1\rangle_1 |L\rangle_1 (|\Phi^2\rangle_1 = |-1\rangle_1 |R\rangle_1$ in path 1 and $|L\rangle_2$ $(|R\rangle_2)$ in path 2. Experimentally, we utilize the setup in Figure \$738 to obtain coincidence counts and then reconstruct the density matrices ρ'_q (q = 1, 2) of state $|\Phi^q\rangle_{12}$ (q = 1, 2) with fidelities as 0.9481 and 0.9242, respectively (Figure 4a). In path 1, Alice1 (Alice2) converts the state $|\Phi^1\rangle_1$ ($|\Phi^2\rangle_1$) in channel i (ii) to one basis state of MUBs $\{|+1\rangle_1|H\rangle_1$, $|+1\rangle_1|V\rangle_1$, $\{|+1\rangle_1|D\rangle_1$, $|+1\rangle_1|A\rangle_1$, $(\{|-1\rangle_1|H\rangle_1, |-1\rangle_1|V\rangle_1$, $\{|-1\rangle_1|D\rangle_1, |-1\rangle_1|A\rangle_1\}$. Bob1 (Bob2) projects the received state in path 1 onto one basis state of the MUBs and the photon in path 2 onto $|L\rangle_2$ ($|R\rangle_2$) to obtain coincidence count.³⁸ By taking the coincidence counts into eq S4,³⁸ we obtain the quantum bit error rate (QBER) Q.⁶ Using these coincidence counts, we then determine the secret key rate *R* by considering the finite-size effects.³⁸ Based on the normalized coincidence counts from the probability-of-detection matrix (Figure 4b), we obtain the QBER to be $Q_1 = 0.2\%$ when using $|\Psi^1\rangle_{12}$ and $Q_2 = 0.2\%$ when using $|\Psi^2\rangle_{12}$.³⁸ Correspondingly, the secret key rates are $R_1 = 0.95$ bits per sifted key for $|\Psi^1\rangle_{12}$ and $R_2 = 0.94$ bits per sifted key for $|\Psi^2\rangle_{12}$.³⁸ These results confirm that the biphoton SAM–OAM hybrid state $|\Psi^q\rangle_{12}$ (q = 1, 2) can be securely applied in the BB84 protocol.

BBM92 Protocol. Within the same platform, we also testify the metasurface-based BBM92 protocol with the hybrid state $|\Psi^q\rangle_{12}$ (q = 3, 4) (Figure 1b). The entangled state $|\Phi^q\rangle_{12} = (|+1\rangle_1|L\rangle_2 - |-1\rangle_1|R\rangle_2)/\sqrt{2}$ is prepared by projecting the photon in channel w (w = iii, iv) onto $|H\rangle_1$. Using the



Figure 3. Real and imaginary parts of the reconstructed density matrices ρ_q of the four SAM–OAM hybrid states $|\Psi^q\rangle_{12}$ generated by the fabricated metasurface: (a) q = 1, (b) q = 2, (c) q = 3, and (d) q = 4.



Figure 4. Experimental proof-of-principle BB84 protocol with SAM– OAM hybrid states $|\Psi^q\rangle_{12}$ (q = 1, 2). (a) The real and imaginary parts of reconstructed density matrices ρ'_q (q = 1, 2). (b) Experimentally measured probability-of-detection matrices for the MUBs corresponding to the channel q = 1, 2.

experimental setting in Figure S8,³⁸ we obtain the coincidence counts and reconstruct the density matrices ρ'_q (q = 3, 4) of state $|\Phi^q\rangle_{12}$ (q = 3, 4) with fidelities 0.9090 and 0.9358, respectively (Figure 5a).³⁸ To prove that the state $|\Phi^q\rangle_{12}$ is entangled, a Hermitian operator \hat{W}' as entanglement witness is introduced. ^{51,52} Once $\text{Tr}(\hat{W}'|\Phi^q\rangle\langle\Phi^q|) < 0$ is satisfied, the state $|\Phi^{q}\rangle_{12}$ is entangled. Here, the experimental values of $\operatorname{Tr}(\hat{W}'|\Phi^q\rangle\langle\Phi^q|)$ are -0.4394 for q = 3 and -0.4547 for q =4, indicating the generation of entangled state $|\Phi^q\rangle_{12}$ (*q* = 3, 4) in the experiment.³⁸ Alice selects the polarization basis of MUBs $\{|L\rangle_2, |R\rangle_2\}$, $\{|H\rangle_2, |V\rangle_2\}$, and Bob selects the OAM basis of MUBs $\{|+1\rangle_1, |-1\rangle_1\}, \{|d\rangle_1, |a\rangle_1\}$ for projective measurements, resulting in coincidence counts. Here $|d\rangle$ = $(|+1\rangle + |-1\rangle)/\sqrt{2}$ and $|a\rangle = (|+1\rangle - |-1\rangle)/\sqrt{2}$. The coincidence counts are taken into eq S838 to obtain the QBER.⁵³ Then, the secret key rate (R) is determined by considering the finite-size effects.³⁸ Based on the normalized coincidence counts in the probability-of-detection matrix (Figure 5b), the QBER is $Q_3 = 2.0\%$ and the secret key rate is $R_3 = 0.54$ bits per sifted key when using the state $|\Psi^3\rangle_{12}$;³⁸ for $|\Psi^4\rangle_{12}$, the QBER turns out to be $Q_4 = 2.7\%$ and the secret key rate is $R_4 = 0.47$ bits per sifted key.³⁸ Since R > 0, this confirms that the states $|\Psi^{q}\rangle_{12}$ (q = 3, 4) are viable for use in the BBM92 protocol.

In a quantum information network, different protocols possess distinct advantages and limitations. For example, the BB84 protocol is more versatile and extensively studied.⁵⁴ It possesses a higher secret key rate, 55,56 adapts to different network topologies, and provides a high level of security.^{14,54} The BBM92 protocol, on the other hand, is more straightforward to implement since the entangled states have inherent randomness. However, the BBM92 protocol is generally limited in its vulnerability to detection attacks and the types of keys it can transmit.⁵⁷⁻⁵⁹ Integrating mQKD in a network can enhance flexibility to optimize performance and increase the reliability of communication.^{60,61} However, the conventional approach may require single photon sources, entanglement sources, beam splitters, waveplates, optical switches, etc. Here, we significantly simplify the system by introducing the interaction of the polarization-entangled photon pair with a metasurface. Currently, by using the metasurface, we have experimentally demonstrated the generation and distribution



Figure 5. Experimental proof-of-principle BBM92 protocol with SAM–OAM hybrid states $|\Psi^q\rangle_{12}$ (q = 3, 4). (a) The real and imaginary parts of reconstructed density matrices ρ'_q (q = 3, 4). (b) Experimentally measured probability-of-detection matrices corresponding to projecting $|\Phi^q\rangle_{12}$ onto the MUBs for channel q = 3, 4.

of four SAM–OAM hybrid states to eight point-to-point connected users for different QKD protocols. Via designing metasurfaces with more output channels, more hybrid states can be generated, thereby supporting more users in the mQKD. Practically, even in the dielectric metasurface, the loss still exists, which may reduce fidelity, increase the QBER, and lower the secret key rate in QKD. However, our results indicate that the transmittance of the channels in our silicon metasurface at a wavelength of 810 nm exhibits a loss of less than 1.6 dB, which is practically acceptable in applications. Moreover, the silicon metasurface is compatible with current semiconductor manufacturing techniques.

Notably, this work serves as a foundational demonstration of basic principles. In practical engineering, a key consideration is the distance over which a quantum key can be reliably distributed. Long-distance transmission of OAM-carrying states has been experimentally achieved in both freespace^{5,6,10} and optical fiber systems.^{4,62,63} Our proof-ofprinciple experiments confirm the feasibility of our mQKD scheme. In ref 38, we demonstrate the transmission of photons with SAM-OAM hybrid states in the BB84 and BBM92 protocols on a meter scale using commercially available optical fibers. With optimized optical fibers and a more efficient light source, significantly longer transmission distances can be expected. In addition, we emphasize that this strategy is not limited to BB84 and BBM92 protocols. It can be applied to other prepare-and-measure QKD protocols, such as the T12, B92, and six-state protocols,⁶⁴ where the desired multiple single-photon states can be generated from a multichannel metasurface. This scheme also applies to other entanglementbased QKD protocols, such as the E91 protocol,^{34,38} where the desired entangled states can be output from a well-designed metasurface. Hence, multiple quantum states (entangled or

unentangled) generated by a well-designed metasurface can be used for mQKD protocols to meet different user requirements, including the acquisition of high secret keys and enhancement of the security levels. Those quantum states can also be distributed on-demand to users to handle other quantum information processes such as quantum secret sharing and quantum teleportation.

To summarize, we demonstrate that multiple SAM–OAM hybrid states can be generated via the polarization-entangled photon pair interacting with a metasurface and efficiently used for multiuser mQKD. The high secret key rate and low quantum bit error rate of the SAM–OAM hybrid states $|\Psi^q\rangle_{12}$ have been achieved. In the trend of miniaturization and integration of quantum information systems, our approach demonstrates a significant step forward in replacing bulky and complicated combinations of conventional optical components in setting up point-to-multipoint links for quantum networks.

METHODS

Metasurface Fabrication. Via plasma-enhanced chemical vapor deposition (PECVD), a layer of amorphous silicon first was deposited on indium tin oxide (ITO)-coated glass. Then, a layer of photoresist (polymethyl methacrylate, PMMA) was spin coated. The patterns were introduced by electron beam lithography (Raith, e-Line). The sample was developed for forming an inverse pattern. A thin Al_2O_3 layer was deposited by electron beam evaporation, followed by chemical lift-off to remove the photoresist, leaving Al_2O_3 patterns. Silicon dry etching with SF₆ and C₄F₈ (3:4 ratio) used Al_2O_3 patterns as the mask, creating silicon nanopillars capped with Al_2O_3 and removing unprotected silicon, resulting in a silicon metasurface.

Classical Optical Characterization of Metasurface. The optical platforms (Figure S3b,c) were built to measure the intensity and phase distributions. For details, see Section 3 in the Supporting Information.³⁸

Biphoton Hybrid State Characterization. The biphoton hybrid states were generated and characterized based on the experimental setup shown in Figure S6. For details, see Section 5 in the Supporting Information.³⁸

Experiments for Using Hybrid States in BB84 Protocol. The experimental setup for the proof-of-principle BB84 protocol with $|\Psi^1\rangle_{12}$ ($|\Psi^2\rangle_{12}$) is shown in Figure S7. For details, see Section 6.1 in the Supporting Information.³⁸

Experiments for Using Hybrid States in BBM92 Protocol. The experimental setup for the proof-of-principle BBM92 protocol with $|\Psi^3\rangle_{12}$ ($|\Psi^4\rangle_{12}$) is shown in Figure S8. For details, see Section 6.2 in the Supporting Information.³⁸

ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available free of charge at https://pubs.acs.org/doi/10.1021/acs.nanolett.5c00868.

Design metasurface for generating biphoton hybrid states; Fabrication of the silicon metasurface; Classical optical characterization of metasurface; Single photon characterizations of metasurface; Generation and measurement of biphoton hybrid states; Experiments for quantum key distribution with hybrid states (free space); Experiments of exploring our scheme in longdistance transmission (fiber); Metasurface-based E91 protocol (PDF)

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Author Contributions

R.P., Y.J., and M.W. conceived this work. Y.J. fabricated the sample with the assistance of W.-J.T. and Z.Y.W. Y.J., R.Z., and H.-L.Z. performed the photonic experiments with the help of Z.W., Y.-F.L., R.-H.F., and D.-X.Q. Y.J. did the optical simulations. R.P. and M.W. directed the experiments and simulations. Y.J., M.W., and R.P. wrote the manuscript.

Notes

The authors declare no competing financial interest.

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