Photon transport enhanced by transverse Anderson localization in disordered superlattices

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Controlling the flow of light at subwavelength scales provides access to functionalities such as negative or zero index of refraction, transformation optics, cloaking, metamaterials and slow light, but diffraction effects severely restrict our ability to control light on such scales. Here we report the photon transport and collimation enhanced by transverse Anderson localization in chip-scale dispersion-engineered anisotropic media. We demonstrate a photonic crystal superlattice structure in which diffraction is nearly completely arrested by cascaded resonant tunnelling through transverse guided resonances. By modifying the geometry of more than 4,000 scatterers in the superlattices we add structural disorder controllably and uncover the mechanism of disorder-induced transverse localization. Arrested spatial divergence is captured in the power-law scaling, along with exponential asymmetric mode profiles and enhanced collimation bandwidths for increasing disorder. With increasing disorder, we observe the crossover from cascaded guided resonances into the transverse localization regime, beyond both the ballistic and diffusive transport of photons.

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\begin{equation}
-\nabla^2 E + \mathbf{V} \cdot \mathbf{E} - \frac{\omega^2}{c^2} \varepsilon_{\text{mat}}(\mathbf{z}) \mathbf{E} = \varepsilon_{\text{ph}} \frac{\omega^2}{c^2} \mathbf{E}
\end{equation}
also been modelled numerically and observed experimentally. In these high-index disordered superlattices, we demonstrate that the resulting transverse guided resonances, with disorder-induced inhomogeneous spectral broadening, can potentially provide improved collimation bandwidth while experiencing, within this frequency range, transverse localization.

Figure 1 shows the nanofabricated chip-scale anisotropic superlattices examined in our study, consisting of alternating layers of photonic crystal sections of thickness $d_1$, made of circular holes arranged in a two-dimensional hexagonal lattice with lattice constant $a = 500$ nm, and homogeneous sections of medium with thickness $d_2$ for a superperiod, $A = d_1 + d_2$. To introduce structural disorder, three other structures are also nanofabricated: heptagonal-hole superlattices (HHS; approximately 2% disorder), square-hole superlattices (SHS; approximately 6% disorder) and triangular-hole superlattices (THS; approximately 13% disorder). In each of these superlattices, disorder is introduced by randomly rotating each scatterer with a stochastically uniform distribution.

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The thickness of the homogeneous section satisfies the relation $d_1/d_2 = 0.18$, with the superlattice band structures, computed along the $\Gamma-X$ direction of the superlattice, shown in Fig. 1f and Supplementary Information I. Significantly, as the superlattice band structure suggests, our photonic structure possesses nearly flat bands (highlighted in red) at the normalized frequencies of 0.314 and 0.327 (in dimensionless units of $\omega a/2\pi c$; centred around 0.322) at $k_x = 0$, corresponding to the high-symmetry $\Gamma$ point. These flat bands represent leaky guided resonances (located outside the light cone), which propagate transversely in the one-dimensional (1D) homogeneous dielectric region that forms a 1D photonic crystal waveguide (in dashed white lines in Fig. 1b–e) separating the photonic crystal sections of the superlattices. The underlying mechanism that leads to enhanced collimation in these superlattices is as follows: mutual coupling of the two leaky guided resonances excited at the input and output interfaces of a homogeneous section gives rise to the mode splitting seen in the red-highlighted bands of Fig. 1f. The $|E|^2$-field profiles of these resonances are shown in the insets of Fig. 1f. Bloch modes of the photonic crystal couple to these guided resonances and are resonantly amplified when tunnelling from one photonic crystal section to the next. This mechanism of resonant wave tunnelling via excitation of guided resonances enhances the diffraction-free beam collimation because the evanescent part of the optical field is propagated through the superlattice as well. This beam collimation mechanism based on resonant tunnelling—from guided resonances to guided resonances—is markedly different from that investigated in earlier studies, in which case the beam divergence is reduced by designing flat spatial dispersion surfaces or by alternating metamaterials layers of normal and anomalous dispersion (see Supplementary Information I to III for detailed design of the superlattices).

To quantify the degree of beam collimation, in Fig. 2 we show the computed effective beam width, $\omega_d = P^{-1}$, defined as the inverse participation ratio, $P(z) = [\int I(x,z)^2dx]/[\int I(x,z)dx]^2$ (ref. 10), where $I(x,z)$ is the field intensity. In these calculations we employed 3D finite-difference time-domain (FDTD) simulations (see Methods and Supplementary Information IV) performed across the 1,500 nm to 1,600 nm spectral domain with 5 nm

Figure 1 | Ordered and disordered superlattices. a, Example of nanofabricated silicon photonic superlattices with 20 superperiods and a single-mode input waveguide, imaged using a focused ion beam. Inset: on-chip input waveguide with a one-by-four splitter to four parallel superlattices for normalization. b, Ordered superlattices with circular holes. The dashed white lines depict the homogeneous region of the superlattices. c, Structural disorder is introduced by replacing the circular holes with heptagonal holes (approximately 2% structural disorder), and rotating them through an angle prescribed by a uniform random distribution. d, As c but with square holes (approximately 6% structural disorder). e, As c but with triangular holes (approximately 13% structural disorder). f, Band structure of the circular-hole superlattices, for the transverse wavevector component $k_y$. Inset: the flat bands (highlighted in red) near the normalized frequencies of approximately 0.314 and 0.327 correspond to two guided resonances excited in the transverse photonic crystal waveguides (top and bottom insets, respectively) with the computed $|E|^2$-profile plotted.
resolution. The blue regions in Fig. 2 indicate the regions of tightest collimation; for our designed circular-hole superlattices (CHS), the collimation band is centred at 1,550 nm. With increasing disorder, the heptagonal-hole superlattices (HHS), Square-hole superlattices (SHS) and Triangular-hole superlattices (THS) structures show significantly larger bandwidths for collimation than does the CHS, as shown in Fig. 3. This is attributed to the inhomogeneous spectral broadening of the guided resonances induced by disorder. The frequency of the guided resonances at the point is shifted by a random amount owing to the coupling of the optical mode with the adjacent, randomly perturbed photonic crystal sections of the superlattices\(^1\), an effect that is also accompanied by increased radiation losses. Because the frequency dispersion of these tunnelling channels increases with disorder, the enhanced collimation bandwidth increases with disorder level as well. We note that in the instance of the rotated SHS the spectral region of strong collimation is slightly blueshifted with respect to the CHS owing to the fact that, even if the hole area is kept the same, the frequency dispersion of the guided resonances depends weakly on the hole shape.

Encouraged by these theoretical predictions, we examined the far-field infrared scattering for 900 wavelengths (1,530 nm to 1,620 nm with 100 pm spectral resolution), for each of the superlattices. Figure 4a highlights the key features, with further supporting examples shown in Supplementary Information V. For the CHS, the most effective collimation is observed at 1,550 nm (\(\lambda_{ec}\)), with the beam width at the interfaces, \(\omega_{THS,ec}\), fluctuating by less than \(\pm 7\%\). This wavelength is closest to that of the guided resonances, allowing more effective coupling, with larger tunnelling transmission and amplification of the evanescent part of the field. This is supported by the spectral analysis of the spatial full-width at half-maximum (FWHM), \(\omega_{THS,ec}\), with the smallest beam width observed at \(\lambda_{ec}\) and matching well with the numerical simulation data, where the strongest collimation occurs in the region of \(\lambda_{ec} = 4\) to \(\lambda_{ec} = 4\) nm.

Figure 4a also shows the electromagnetic propagation for the disordered HHS, SHS and THS cases at the corresponding \(\lambda_{ec}\) wavelengths, compiled from 2,700 scattering images. Collimation is observed even in these disordered superlattices. The most effective \(\lambda_{ec}\) wavelengths are determined to be approximately 1,550 nm (HHS), 1,555 nm (SHS) and 1,580 nm (THS), respectively. At other wavelengths, the beam diverges significantly from its input excitation bandwidth in the disordered superlattices. Concurrently, the larger-disorder superlattices, such as the triangular and square realizations, show shorter transmission lengths owing to the increased disorder scattering losses from the perturbed Bloch modes. To observe finer features in the \(z\)-direction, we next perform near-field scanning optical microscopy (NSOM) at the \(\lambda_{ec}\) wavelengths to probe the local field intensity oscillations in each superlattice (see Supplementary Information VI). Mapping the near-field intensity with the superimposed photonic crystal topography, the periodic enhancement of the wave scattering is determined to be centred at the location of the transverse waveguides. These near-field measurements (calibrated with a periodic topography grid) also show the \(z\)-thin, \(x\)-long scattering slices corresponding to the thin homogeneous transverse waveguides. With increasing disorder, the near-field intensities at the interfaces become increasingly apparent compared to the background stray light (see Supplementary Fig. 13) owing to
the increased scattering into the radiation continuum and the more efficient excitation of the guided modes.

To compare against the guided resonances approach, we next designed photonic crystals with sizes of a few hundred micrometres$^2$–4, but without the superlattices and with flat equifrequency dispersion curves. We nanofabricated and examined, under the same conditions, collimation in these lattices, as detailed in Supplementary Information VII. Figure 4b shows the observed beam propagation at $\lambda_c$ in the presence of disorder, in the collimation regime. The field profiles in Fig. 4b clearly demonstrate that in this case beam collimation is of a markedly different nature, as it almost completely vanishes in the presence of disorder. The averaged collimating beam width increases from approximately 2.2 $\mu$m to approximately 2.5 $\mu$m (heptagon hole), 6.8 $\mu$m (square hole) and 13.9 $\mu$m (triangular hole), without the guided resonance contributions. The fluctuation of the beam width increases from $\pm$5% to $\pm$6% (heptagon hole), $\pm$9% (square hole) and $\pm$11% (triangular hole).

Figure 5 shows the optical wave transport in the superlattices at different wavelengths, for different disorder. The physical nature of the electromagnetic propagation is revealed by the slope of the function $\omega_{\text{phym}}(z)$ when represented on a log–log scale. As shown in the log–log plots of Figs. 6a to d, the asymptotic dependence of the experimental effective $\omega_{\text{phym}}$ is of the form $\omega_{\text{phym}}(z) \propto z^\nu$, where the slope $\nu$ is a power exponent determined by linear fitting. For the CHS in Fig. 6a, we observe $\nu$ values up to 0.24 at the longer wavelengths, but with a near-zero slope $\nu \approx 0.05$ between $\lambda_c - 4$ to $\lambda_c +4$ nm. This corresponds to an approximately 8 nm collimation bandwidth and is due solely to the beam interaction with the guided resonances. In the presence of roughly 2% and 6% structural disorder (HHS and SHS, respectively), however, the measured log–log plots of $\omega_{\text{phym}}(z)$ show a markedly different spectral dependence. The slope $\nu$ decreases significantly in the HHS between $\lambda_c - 4$ and $\lambda_c + 17$ nm, and in the SHS between $\lambda_c - 4$ and $\lambda_c + 17$ nm. This is shown in Figs 6b and c, respectively. In both superlattices a near-zero $\nu$ value of $\approx 0.05$ is now achieved within a 21 nm collimation bandwidth, sizably larger than in the CHS.

The observed increased collimation arises from the disorder-induced inhomogeneous spectral broadening of guided resonances. To further support this, we next examined the CHS structure, with larger (approximately 13%) structural disorder. The analysed experimental collimation bandwidth is even larger, namely approximately 31 nm ($\lambda_c - 7$ to $\lambda_c + 24$ nm), as shown in Fig. 6d. These observed near-zero $\nu$ bandwidths are also larger (and outside) the bandwidth of the computed regular CHS without disorder, with an approximately 3.9 times increase in collimation bandwidth achieved experimentally in the presence of disorder as compared to the periodic disorder-free CHS. We also note that, to characterize the effects of disorder, an ensemble average is needed over different realizations of disorder; in our superlattices the ensemble average is self-consistently performed as the beam propagates over 20 disordered photonic crystal sections of the superlattices—each of the supercells having the same level of randomness but a different disorder realization. Furthermore, in the numerical modelling results, we note that in the high-index physical setting studied here we described the optical beam propagation with the 3D vectorial Maxwell’s equations instead of a Schrödinger-type equation to account for the wave dynamics. The measured bandwidth increase of nearly zero $\nu$ with increasing disorder is also supported by our 3D simulations, both in terms of the general wavelength dependence of $\nu$ and its estimated bandwidth from disorder. We note the localization bandwidth computation is a higher-order analysis, especially with the disorder lattice models of $\sim 4,000$ or more scattering sites, where there are slight deviations between the exact numerical and experimental lattice instances, and with the experimental samples containing additional disorder sources (such as from the sidewall roughness) that can account for the measured larger bandwidths.

This phenomenon of disorder-induced enhanced beam collimation is reminiscent of transverse localization. In isotropic media, ballistic transport is characterized with $\nu = 1$ and diffusive transport is characterized with $\nu = 1/2$; our measurements and simulations clearly demonstrate that the photon transport is arrested by disorder with $\nu$ values predominantly less than 0.05 in our disordered superlattices, even exceeding that of circular regular lattices. For the largest disorder (THS), we observed the strongest localization with consistently near-zero $\nu$ values, averaged at 0.017, and with an almost flat spectral dependence of $\nu$. In this regime for all disordered superlattices, the beam is localized and its divergence is arrested by the structural disorder in the superlattices, subject only to statistical fluctuations in the scattering sites. The observed transverse localization arises from multiple coherent scattering of light induced by the disordered potential, forming localized guided resonances at the homogeneous–photonic crystal interfaces. We also note that fluctuations in $\omega_{\text{phym}}$ increase with disorder (images in Supplementary Information V) and are consequently inversely proportional to the dimensionless conductance $\Sigma_c \approx \rho(\omega)D_c^{-1}$, with the diffusion coefficient $D_c$ approximately equal to the power exponent slope $\nu$. This reduced dimensionless conductance for increasing disorder arises owing to coherent backscattering in the guided resonances over macroscopic length scales.

We further confirm the transverse localization through an analysis of the transverse intensity beam profile and its $z$–axis spatial progression. This is performed by examining the transverse intensity profile fitted to an exponentially decaying form $I \sim \exp(-2|x|/\xi)$.
Increasing disorder
ab Circular Heptagonal Triangular Square
Increasing disorder 
5 µm
Millimetre-scale

Figure 4 | High-resolution far-field infrared scattering images illustrating photon transport in the disordered superlattices. a, Circular-hole, heptagonal-hole, square-hole and triangular-hole superlattices at the $\lambda_{sc}$ wavelengths. b, Disorder media without superlattices and with a collimation mechanism solely from flat spatial dispersion surfaces. Measurements are shown at the $\lambda_{sc}$ wavelengths in the presence of disorder. Beam widths in these media with scales of a few hundred micrometres increase with increasing disorder, contrary to the superlattices.

where $\xi$ is the localization length (the exponential decay length of the confined modes and defined with $l^* \exp(\pi k T^*/2)$, a characteristic length scale of Anderson localization). For instance, in the case of HHS investigated at $\lambda_{sc} + 17$ nm, our analysis shows that $\xi$ is 25 µm for the $z = 25$ µm location and it roughly preserves an exponential transverse profile (instead of a Gaussian profile, as is the case for diffusive transport). We also note that the beam profile becomes increasingly more asymmetric as disorder increases (as detailed in the Supplementary Information V and Supplementary Fig. 12). The exponential profile is also found to be the best fit for the SHS and THS cases. The exponential profile is a clear indication of chip-scale localization, with wave interference from the interplay of disorder on the periodic lattice.

For the circular superlattices without appreciable disorder, a new type of anisotropic medium based on cascaded excitation of guided resonances is observed, with highly dispersive features and supported by both experimental measurements and numerical modelling. With increasing disorder, beam collimation in heptagonal, square and triangular superlattices are observed for the first time. With increasing disorder strength, we observed increased collimation bandwidth, tighter collimation than in regular circular superlattices, and enhanced transverse localization. Transport in disordered superlattices reaches a regime of almost arrested diffraction, departing significantly from diffusive and ballistic transport, a phenomenon verified by the power-law scaling of the beam width and exponentially decaying asymmetric intensity beam profiles in the localization regimes.

The observed transverse Anderson localization allows us to access values of the collimation bandwidth that are difficult to access through other approaches. By analogy to electronic transport, these observations allow us a means to probe the transverse Anderson localization of photons in solid-state semiconductors, including the role of guided resonances and the localization evolution. Future studies include optical nonlinearity perturbations to the localization (for different disorder levels) with potential spontaneous pattern formation, background scattering potentials with quasicrystal geometries, or the probing of these spatially localized modes with entangled biphoton states. The optical measurements developed here can find applications to other areas of physics as well. For example, photon transport in our superlattices is in many aspects analogous to electron wave dynamics in graphene heterostructures\textsuperscript{26}, so that similar effects could be observed in electron transport in a superlattice of closely spaced disordered graphene nanoribbons\textsuperscript{27}. The role of the guided resonances in this system arises from the nanoribbon edge states. These same phenomena could also be explored in other studied electronic systems, such as semiconductor superlattices\textsuperscript{28} and oxide heterojunctions\textsuperscript{29}, with interface states playing the role of guided resonances. Matter-wave transport in atomic\textsuperscript{30,31} and polariton\textsuperscript{32} Bose–Einstein condensates trapped in suitably designed optical superlattices could also provide fertile testing grounds of the conclusions of our work.

Figure 5 | Disorder-induced enhanced photon transport at the onset of transverse localization. Schematic of infrared scattering for superlattices with different disorder (from left to right): circular, heptagonal, square and triangular scatterers. The colour plots correspond to the different wavelengths shown in the other panels. The beam diverges in the circular-hole superlattices but shows collimation in the heptagonal-hole and square-hole superlattices.
Photon transport enhanced by transverse localization. Figure 6 shows Log-log plots of the experimentally derived effective beam width $\theta_{FWHM}(z)$ versus propagation distance for circular-hole (a), heptagonal-hole (b), square-hole (c) and triangular-hole (d) superlattices, determined from the full-width at half-maximum of the far-field infrared scattering, in the spectral region $\lambda_{ec} \sim 10$ to $\lambda_{ec} + 25$ nm. The red solid lines represent the approximate wavelength for most effective collimation $\lambda_{ec}$ (with least beam divergence; see also Supplementary Information V). Inset: distributions of the slope $\nu$ in the spectral region $\lambda_{ec} \sim 10$ to $\lambda_{ec} + 25$ nm. The green filled dots and black open circles, respectively, represent the experimental and numerical simulation values of $\nu$.

Methods

Device nanofabrication. The photonic crystal structures shown in Fig. 1 were fabricated on a silicon-on-insulator wafer with a single-crystal silicon slab ($n_s = 3.48$) of 320 nm thickness on top of a 2 μm-thick layer of buried oxide ($n_{box} = 1.46$), with electron-beam lithography. ZEP520A (100%) resist was spin-coated at 4,000 revolutions per minute for 45 s to a thickness of ≈350 nm, then baked at 180 °C for 3 min. The JEOL JBX6300FS electron-beam lithography systems at Brookhaven National Laboratory-USA and ELIONIX ELS7500EX at National Cheng Kung University-Taiwan, respectively, were used to expose the ZEP520A resist to define the pattern, followed by development in amyl acetate for 90 s and rinsing with isopropyl alcohol (IPA) for 45 s to completely remove any residue of amyl acetate developer.

An Oxford Instruments Plasmalab 100 was used for pattern transfer onto the silicon layer of the silicon-on-insulator wafer, using an inductively coupled plasma reactive ion etcher (ICP-RIE) to perform the cryogenic silicon etching. O$_3$ at $-100$ °C was applied in the chamber first for cleaning and cooling, followed by cryogenic etching at $-100$ °C using a mixture of SF$_6$ (40 sccm) and O$_2$ (15 sccm) at 15 W radiofrequency (r.f.) power, 800 W ICP power and 12 mtorr pressure for a total of 16 s. The resulting wafer was subsequently placed in a n-methyl pyrrolidone (NMP 1165) resist remover for about 4 h to completely remove the remaining ZEP resist.

Band structure and time-domain numerical simulations. The band diagrams of the photonic crystals and photonic superlattice are computed with the RSoft software BandSOLVE, a commercially available software that implements a plane wave expansion algorithm. In all numerical simulations a convergence tolerance of $10^{-3}$ was used to compute the frequency bands. The photonic bands of the photonic crystal have been divided into TM-like and TE-like polarizations, according to their parity symmetry. The effective refractive indices corresponding to the TM-like bands are determined from the relation $k = \omega/|n|c$, with $k$ in the first Brillouin zone (see Supplementary Information).

The numerical simulations of the intensity field distribution were performed by using the MIT code MEEP, a freely available code based on the finite-difference time-domain (FDTD) method. In all numerical simulations we used a uniform computational grid with 33 grid points per micrometre. This ensures that the smallest characteristic length of the system (in our case, the hole diameter) is sampled by at least ten grid points. In our FDTD simulations we used a continuous wave excitation source of the same transverse size as the input waveguide, placed at the output facet of the waveguide.

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Author contributions
P.H., N.C.P. and C.W.W. conceived the project. P.H. designed the photonic superlattices and performed the theoretical analysis and FDTD numerical simulations. M.T. prepared the NSOM probes. N.C.P. designed the photonic crystal superlattices and carried out focused ion beam imaging. J.F.M. performed the far-field and group velocity measurements. M.T. prepared the NSOM probes. N.C.P. designed the photonic crystal superlattices and performed the theoretical analysis and FDTD numerical simulations. P.H., N.C.P. and C.W.W. conceived the project. P.H. designed the photonic superlattices and performed the theoretical analysis and FDTD numerical simulations. P.H., N.C.P. and C.W.W. wrote the manuscript, which all authors discussed.

Additional information
Supplementary information is available in the online version of the paper. Reprints and permissions information is available online at www.nature.com/reprints. Correspondence and requests for materials should be addressed to P.H., N.C.P. or C.W.W.

Competing financial interests
The authors declare no competing financial interests.