The degree of optical spatial coherence—a fundamental property of light that describes the mutual correlations between fluctuating electromagnetic fields—has been proven challenging to control at the micrometer scale. We use surface plasmon polaritons—evanescent waves excited on both surfaces of a thin metal film—as a means to mix the random fluctuations of the incident electromagnetic fields at the slit locations of a Young’s double-slit interferometer. Strong tunability of the complex degree of spatial coherence of light is achieved by finely varying the separation distance between the two slits. Continuous modulation of the degree of spatial coherence with amplitudes ranging from 0 to 80% allows us to transform totally incoherent incident light into highly coherent light and vice versa. These findings pave the way for alternative methods to engineer flat optical elements with multifunctional capabilities beyond conventional refractive- and diffractive-based photonic metasurfaces.
**Effects of spatial coherence of incident light**

Several wavelength-resolved interference patterns for the same Young's double-slit with $d = 5 \, \mu m$ under varying degrees of spatial coherence of the incident light are reported in Fig. 2. Under TE-polarized illumination (no SPPs), the far-zone interference patterns gradually change as a function of incident wavelength $\lambda$, at any given $\Delta \theta$ (Fig. 2, A to C). Light
with longer wavelength generates interference fringes that are spatially more spread out compared with shorter wavelengths, as the result of the longer optical path difference required to achieve the same phase shift on the projection screen. The fringe visibility is greatly reduced when light with lower degree of spatial coherence (that is, higher subtended illumination angle Δθ) is used. By rotating the polarization state of the incident light by π/2 (that is, from TE to TM), SPPs from both metal/dielectric interfaces can be turned on, and strong modulation of the fringe visibility is observed as the result of additional beatings between the two SPP modes (Fig. 2, D to F). Both the amplitude (related to fringe visibility) and phase (related to either constructive or destructive interference at the screen center) of the degree of spatial coherence are strongly modulated under TM-polarized illumination due to SPP excitation (Fig. 2, E and F) that determines a redistribution of the far-zone light intensity. Both enhancement and suppression of fringe visibility can be achieved relative to the respective interference patterns under TE illumination (Fig. 2, B and C, no SPPs).

Theory of optical coherence modulation with surface plasmons

An analytical expression for the output fields that includes SPP contributions can be written as

$$E_{ij}(λ, d) = \tau E_{in}(λ) + \beta \frac{E_{in}(λ)}{λ^2},$$

where (i, j) = (1, 2) or (2, 1); E_{in} is the incident scalar field at one slit location; τ is the transmission coefficient through the slit; λ is the free-space wavelength of light; and β = β_{spp} λ + β_{r} λ^2, where β_{spp} and β_{r} are the SPP coupling coefficients at the top (that is, glass/Ti/Ag) and bottom (that is, Ag/air) interfaces, respectively, and k_{SPP} and k_{SPP}^{*} are the corresponding SPP complex wave vectors, which account for SPP absorption due to ohmic losses in the metal.

By using the definition of cross-spectral density function $W_{ij}(λ) = \langle E_{i}^*(λ) E_{j}(λ) \rangle$, where the angle brackets indicate ensemble averaging, the degree of spatial coherence of light exiting the double-slit can be written as

$$μ_{out}(λ) = \frac{W_{12}(λ)}{\sqrt{W_{11}(λ) W_{22}(λ)}}$$

$$≈ \frac{μ_{in}(λ) + 2 \text{Re}(β) + |β|^2 μ_{in}^{*}(λ)}{\sqrt{(1 + |β|^2 + 2 \text{Re}[β μ_{in}(λ)]) (1 + |β|^2 + 2 \text{Re}[β μ_{in}^{*}(λ)])}}$$

where μ_{in} is the complex degree of spatial coherence of light incident on the double-slit, which is generally treated as an ad hoc tunable parameter ($21–23$). Here, μ_{in} is experimentally tuned using a Köhler illumination setup in which light with varying degrees of spatial coherence is generated by changing the subtended illumination angle through a variable condenser aperture. Moreover, a theoretical framework is developed to calculate the far-field intensity distribution determined by light diffraction and interference either with or without SPP contributions, as described in the Supplementary Materials.

Beatings between surface plasmons excited on both metal/dielectric interfaces

To better quantify and control the modulation of the complex degree of spatial coherence, SPP contributions from both metal/dielectric interfaces need to be considered and carefully tailored. These contributions can be extracted by analyzing the plasmonic interferogram, that is, a plot of the normalized intensity ratio at a given wavelength obtained by normalizing the light intensity transmitted through each double-slit with varying separation distance to the reference intensity transmitted through the corresponding individual slit ($29$). Figure 3A shows a representative plasmonic interferogram measured at λ = 600 nm. Discrete Fourier transform analysis applied to this data set ($28, 30$) shows the different SPP contributions originating from both Ag/air (black arrows) and glass/Ti/Ag interfaces (red arrows) as distinct intensity peaks in the Fourier power spectrum amplitude (Fig. 3B). This procedure can be extended to all measured wavelengths, and the resulting data sets are plotted as two-dimensional color maps of plasmonic interferograms (Fig. 3C) and Fourier transform power spectra (Fig. 3D), which reveal the energy-momentum dispersion of SPPs existing on both interfaces. By filtering out the higher-order SPP contributions (with m > 1), plasmonic interferograms with only first-order SPP contributions can be reconstructed (red line in Fig. 3A), and the corresponding SPP coupling coefficients β_{spp} and β_{r} can be extracted from fits to the filtered data (see Materials and Methods).

Strong modulation of spatial coherence

Far-zone interference patterns as a function of slit-slit separation distance can be constructed by scanning all of the fabricated Young’s double-slit interferometers with varying separation distances under TE-polarized (Fig. 4, A to C) and TM-polarized (Fig. 4, D to F) illumination. The far-zone interference patterns recorded in the presence of SPPs show strong modulation in the fringe contrast and richer
Fig. 3. Evidencing SPP contributions supported by both metal/dielectric interfaces. (A) Plasmonic interferogram as a function of slit-slit distance measured at $\lambda = 600$ nm (black line). Reconstructed filtered data (red line) and theoretical fits (blue line) are also reported. The distance between adjacent vertical dashed lines is equal to $\lambda_{\text{SPP}}$, that is, the SPP wavelength at the Ag/air interface. (B) Discrete Fourier transform power spectrum calculated from the experimental data in (A), which shows different orders of SPP contributions from both glass/Ti(3 nm)/Ag (red arrows) and Ag/air (black arrows) interfaces. Inset: Schematic of SPPs propagating along both metal/dielectric interfaces and simultaneously affecting the output intensity and far-zone interference pattern. (C) Wavelength-resolved plasmonic interferograms obtained by normalizing the transmission spectra through double-slit interferometers by the reference transmission spectra through individual slits. (D) Energy-resolved power spectra obtained by applying discrete Fourier transform to the data in (C). Energy-momentum dispersion curves evidence the presence of SPPs supported by both Ag/dielectric interfaces [bright bands in (D)] and are in good agreement with calculations (gray lines) based on the dielectric functions of materials.

Fig. 4. SPP-enabled amplitude and phase modulation of complex degree of spatial coherence. (A to F) TE-polarized (A to C) and TM-polarized (D to F) Young’s double-slit far-zone interference patterns measured at $\lambda = 600$ nm as a function of slit-slit distance and for three different Köhler subtended illumination angles ($\Delta \theta = 3^\circ$, $6^\circ$, and $10^\circ$), corresponding to decreasing spatial coherence length ($L_C =$ 3.18, 1.47, and 0.93 $\mu$m, respectively). The color bar refers to normalized interference-fringe intensity on the projection screen. (G to I) Experimental visibility curves extracted from far-zone interference patterns measured under TE-polarized (green lines; no SPPs) and TM-polarized (blue lines; with SPPs) illumination, at $\lambda = 600$ nm, and for different values of $\Delta \theta$. The black lines are the theoretical results for TE illumination obtained by fitting the corresponding experimental data to a sinc function ($\operatorname{sinc}(\frac{k_0 d}{D_q})$), with $\Delta \theta$ as the only fitting parameter. The red lines are the theoretical predictions of visibility under TM illumination calculated using Eq. 1 and including SPPs from both metal/dielectric interfaces. Insets in (I) highlight strong modulation of visibility (and, correspondingly, amplitude of complex degree of spatial coherence) induced by SPPs. (J to L) Experimental TM (blue lines), theoretical TE (gray lines), and theoretical TM (red lines) phase values of complex degrees of spatial coherence for various $\Delta \theta$. For clarity, the red and blue lines are slightly shifted in the vertical direction. Discrete data points sporadically missing from the blue lines correspond to visibility values $V < 0.088$ for which the phase cannot be accurately retrieved.
intensity features, with overall increased number of observable maxima and minima (for instance, compare Fig. 4F with Fig. 4C). The amplitude and phase of the complex degree of spatial coherence at any given wavelength can be extracted from quantitative inspection of the interference patterns. The results of such an exercise are reported in Fig. 4 (G to L), for both TE and TM illumination, at \( \lambda = 600 \) nm. The fringe visibility recorded under TE-polarized (no SPPs) illumination with \( \Delta \theta = 3^\circ \) gradually decreases as a function of increasing slit-slit separation distance (green line in Fig. 4G). Such a change follows the model derived from the van Cittert–Zernike theorem (black line in Fig. 4G). In contrast, the measured visibility under TM illumination (with SPPs) is significantly modulated (blue line in Fig. 4G). Note that for small separation distances \((d < 5 \mu m)\), interference effects caused by beatings of SPPs supported by both metal/dielectric interfaces are visible, as evidenced by the non–single-periodic oscillations of the visibility curve. In contrast, for large separation distances \((d > 5 \mu m)\), the SPPs propagating along the glass/Ti/Ag interface are more strongly attenuated compared to the SPPs supported by both metal/dielectric interfaces are visible, as evidenced by the non–single-periodic oscillations of the visibility curve.

According to Eq. 1, under TE illumination, \( \mu_{\text{out}} = \mu_{\text{in}} \), because SPPs are not excited (that is, \( \beta = 0 \)) and cannot modulate fringe visibility. Thus, the experimental visibility values extracted under TE illumination are a direct measure of the mutual correlation function of the incident light at the slit locations. From this and by using the SPP coupling coefficients obtained from plasmonic interferograms as input parameters in Eq. 1, the amplitude and phase of the complex degree of spatial coherence under TM illumination can be theoretically predicted (red lines in Fig. 4, G and J). The theoretical values agree well with the experimental results over the whole range of visibility, wavelength, and slit-slit separation distance (see the Supplementary Materials for more details).

**DISCUSSION**

As highlighted in the first inset of Fig. 4I, by finely varying the slit-slit separation distance within a range of only \( \sim \lambda_{\text{SPP}}/2 \approx 240 \) nm, with \( \lambda_{\text{SPP}} \) as the average SPP wavelength at \( \lambda = 600 \) nm, the experimental visibility can be varied from \(-0.6\) (totally incoherent) to \(-0.8\) (almost fully coherent) under TM illumination. Furthermore, as shown in the second inset of Fig. 4I, by simply changing the polarization state from TE (green lines; no SPPs) to TM (blue lines; with SPPs), fully incoherent incident fields can be transformed into highly correlated \((\theta = 0)\) or anticorrelated \((\theta = \pi)\) fields with \( V > 0.4\). Compared with a previous work (23), higher SPP coupling coefficients achieved by tuning the width of each slit enable stronger amplitude modulation of spatial coherence. In contrast, the presence of SPPs on both interfaces can also be used to finely modulate the phase of the complex degree of spatial coherence, as shown in Fig. 4 (K and L).

In principle, dense arrays of nanoslits, nanoholes, or other nanostructures in metal films may be designed to modify the spatial coherence of an entire light beam (20). As an alternative to SPPs supported by corrugated, lossy metal surfaces, photonic modes in planar waveguides coupled with dielectric metasurfaces may also be used to strongly modify the spatial coherence of incident light, which can lead to beam–transforming optical elements with significantly lower transmission losses.

In summary, we have achieved full control of the complex degree of spatial coherence of light at the micrometer scale using surface plasmon–based interferometers. Strong modulation of the amplitude and phase of the complex degree of coherence is accomplished by engineering the beatings between the surface plasmons with different wave vectors generated at the two metal/dielectric interfaces. These findings can lead to alternative nanoengineered optical flat surfaces that leverage the degree of spatial coherence to achieve ultimate control of light flow, which is beyond conventional refractive- and diffractive-based photonic metasurfaces.

**MATERIALS AND METHODS**

**Sample fabrication**

Electron beam evaporation was used to deposit an approximately 200-nm-thick layer of silver (Ag) on one of the two surfaces of a 1-mm-thick glass slide that was previously coated with a 3-nm-thick titanium (Ti) layer to improve film adhesion. Multiple Young’s double-slit interferometers, consisting of two identical \(-200\)-nm-wide, \(-200\)-nm-deep, and \(-15\)-\(\mu m\)-long slits, with variable slit-slit separation distance, were etched on the silver film using focused ion beam milling (fig. S2). The slit width was chosen to provide comparable transmission intensity under both TE and TM illumination and high SPP coupling coefficients. The separation distance between the two slits ranged from 0.5 to 9.525 \(\mu m\) in incremental steps of 25 nm. In total, 362 Young’s double-slit interferometers were etched on the metal film, evenly distributed in two separate columns. A single column containing 181 identical individual slits was also etched on the same silver film to serve as reference for normalizing light transmission through the double-slits. The columns of single- or double-slits were placed 600 \(\mu m\) apart, and adjacent slits along each column were separated by 25 \(\mu m\) to avoid optical cross-talk during the measurements that could affect the interference patterns and lead to artificially reduced visibility values.

**Optical characterization**

Köhler illumination was used to achieve variable spatial coherence illumination of Young’s double-slit interferometers. The setup consisted of a xenon arc lamp, coupled to an inverted microscope, together with a diffuser, an auxiliary lens, a linear polarizer, a 2-mm-wide slit mask, and a condenser lens system (28). Each interferometer was illuminated from the glass side—that is, from the glass(1 mm)/Ti(3 nm)/Ag(200 nm) interface—and the transmitted light intensity was collected with a 20× objective (numerical aperture, 0.75) from the opposite side, that is, from the Ag(200 nm)/air interface. The focal plane of the objective lens was located \(-49\) \(\mu m\) below the metal surface containing the double-slit interferometers to generate far–zone projections of light intensity onto the imaging plane of a charge-coupled device (CCD) camera. More specifically, the interference pattern was projected onto the entrance slit mask of a spectrograph, dispersed by a grating with 150 grooves/mm, and imaged onto a two-dimensional CCD camera to extract the wavelength dependence of light intensity along the horizontal axis and the spatial intensity distribution along the vertical axis (see Fig. 1). This experimental setup allows the detection of wavelength–resolved interference patterns transmitted through each Young’s double-slit interferometer, from which the fringe visibility over several wavelengths can be captured simultaneously in a single CCD image. By scanning all of the double-slit interferometers with different separation distances using an automated microscope stage, 362 wavelength–resolved interference patterns were obtained for each subtended angle and for TE (that is, no SPPs) or TM (that is, with SPPs) polarization states of the incident light (fig. S3). In addition, a full set of light transmission experiment was also performed for all the double-slits and reference single-slits by focusing the microscope objective directly onto the output metal film surface to measure plasmonic interferograms necessary to determine SPP excitation, propagation, and coupling coefficients for both top (glass/Ti/Ag)
and bottom (Ag/air) interfaces as a function of incident wavelength. Note that a Nikon Perfect Focus System was used during the scanning process to keep a constant relative distance between the microscope objective and the bottom sample surface (that is, Ag/air interface). All interference patterns (Figs. 1, 2, and 4 and figs. S3 and S6) were normalized to the corresponding mean intensity value at each wavelength to remove the wavelength-dependent intensity variation introduced by the external light source.

**Supplementary Text**

**Supplementary Materials**

Supplementary material for this article is available at http://advances.sciencemag.org/cgi/content/full/3/10/e1700133/DC1

**Fig. S1.** Role of angle of incidence and subtended angle in Young’s double-slit interference patterns under Köhler illumination.

**Fig. S2.** Scanning electron microscopy images of Young’s double-slit interferometers and subtended illumination angles at two different polarizations. The light spectra transmitted through the double-slits ($I_{DS}$) and reference single-slits ($I_{SS}$) were measured by focusing the objective onto the nanoapertures. The scalar field transmitted through the single-slit ($E_{SS}$) and double-slit ($E_{DS}$) can be expressed as follows

$$E_{SS} (\lambda) = \tau E_{in} (\lambda)$$

$$E_{DS} (\lambda, d) = \tau E_{in} (\lambda) + \tau B E_{in} (\lambda)$$

where the field incident on each slit is assumed to be the same ($E_{in}$), and the two incident fields on the slits can be considered fully coherent up to a 5-μm separation distance under the subtended illumination angle $\Delta \theta \approx 3^\circ$ (corresponding to $\mu_{in} \geq 0.7$). Accordingly, the normalized intensity ratio of the transmitted intensity through the double-slit and reference single-slit can be written as

$$I_n (\lambda, d) = \frac{I_{DS} (\lambda, d)}{I_{SS} (\lambda)} = \frac{E_{DS} (\lambda, d)^2}{E_{SS} (\lambda)^2} = \left| 1 + B^2 \right|^2$$

where the factor 2 in the denominator arises from the fact that the two slits in the Young’s double-slit interferometer can be fully distinguished by the optical setup; therefore, the intensity (rather than the fields) can be summed up when the two slits are directly imaged.

A representative plasmonic interferogram at $\lambda = 600$ nm is plotted in Fig. 3A (black line). The wavelength-resolved plasmonic interferograms are shown in Fig. 3C. By applying discrete Fourier transform to plasmonic interferograms, different orders of SPP contributions can be deconvolved (28, 30), as shown by the peaks and bright bands in Fig. 3 (B and D), which are in good agreement with the calculated wave vectors of different orders of SPP (gray lines in Fig. 3D). SPP contributions from both interfaces (black versus red labels) were evident. After filtering out higher-order SPP contributions (that is, with $m > 1$), plasmonic interferograms that only originate from first-order SPPs can be reconstructed (red line in Fig. 3A). By fitting the reconstructed plasmonic interferograms (with $d$ ranging from 1 to 5 μm) to Eq. 4, SPP coupling coefficients $\beta (\lambda)$ and $\beta_b (\lambda)$ can be extracted (see fig. S7). Thus, the modulation of the visibility in Fig. 4 can be theoretically predicted using Eq. 1, provided that the visibility of the incident fields is known.

**Fig. S3.** Experimental, wavelength-resolved interference patterns for representative Young’s double-slit interferometers and subtended illumination angles at two different polarizations.

**Fig. S4.** Estimate of effective optical width of individual slits.

**Fig. S5.** Comparison between visibility curves obtained using numerical integration and analytical expressions.

**Fig. S6.** Comparison between theoretical and experimental Young’s double-slit interference patterns for micrometer-scale slit-slit separation distances.

**Fig. S7.** Coupling coefficients of SPPs excited along both metal/dielectric interfaces.

**Fig. S8.** Representative visibility curves.

**Fig. S9.** Experimental SPP energy-momentum dispersion curves.

**Fig. S10.** Fourier transform analysis.

**References** (J1, J2)

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