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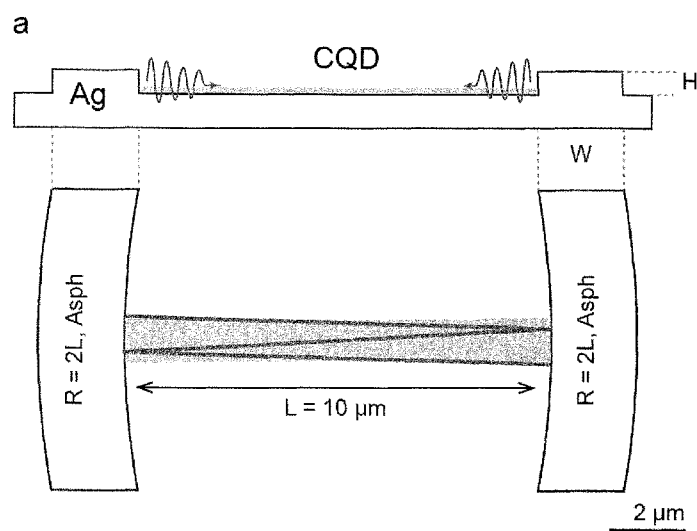


FIG. 4

(57) Abstract: A method of making a plasmonic device, or plasmonic chip, the method comprises the following steps: patterning a metallic surface; incorporating gain material for creating coherent surface plasmon polaritons or localized surface plasmons at desired locations; and incorporating further elements on the surface to manipulate these surface plasmons for a desired purpose.

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TITLE

**SPASERS, PLASMONIC LASERS, PLASMONIC AMPLIFIERS, AND
METHODS FOR MANUFACTURING SAME**

5

TECHNICAL FIELD

Devices and methods in accordance with the present invention refer to U.S. Patent Nos. 8,948,562 and 9,356,238, both by Norris et al., and both entitled “Replication of Patterned Thin-Film Structures for Use in Plasmonics and Metamaterials.”

10

PRIOR ART

Modern information and sensor technologies depend on the intense, coherent, and monochromatic output of lasers. When this light is processed by miniaturized photonic circuits, applications can benefit from more efficient designs, improved performance, and quantum-mechanical effects (J. L. O'Brien, A. Furusawa, J. Vuckovic, *Nature Photonics* **3**, 687 (2009)). However, due to the diffraction-limit of light, photonic circuits are intrinsically larger than electronic devices with which they must interface. A possible route to miniaturization is provided by plasmonic circuits (V. J. Sorger, R. F. Oulton, R. M. Ma, X. Zhang, *MRS Bulletin* **37**, 728 (2012)), which manipulate signals based on surface-plasmon polaritons (SPPs)—photon-like electromagnetic waves that can be focused to the nanoscale (W. L. Barnes, A. Dereux, T. W. Ebbesen, *Nature* **424**, 824 (2003); D. K. Gramotnev, S. I. Bozhevolnyi, *Nature Photonics* **4**, 83 (2010); D. K. Gramotnev, S. I. Bozhevolnyi, *Nature Photonics* **8**, 13 (2014)). For this approach to be technologically viable, plasmonic lasers, or “spasers”, are needed as coherent on-chip sources of SPPs (M. I. Stockman, *Nature Photonics* **2**, 327 (2008); M. I. Stockman, *Optics Express* **19**, 22029 (2011); P. Berini, I. De Leon, *Nature Photonics* **6**, 16 (2012)), but designs to date (R. M. Ma, R. F. Oulton, V. J. Sorger, X. Zhang, *Laser & Photonics Reviews* **7**, 1 (2013)) cannot be incorporated into larger circuits, hindering the development of integrated plasmonics.

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SUMMARY OF THE INVENTION

The invention described herein provides a new class of versatile spasers that generate SPPs under ambient conditions (room temperature and air at atmospheric pressure) at desired locations on a planar chip, allowing easy integration with other circuit elements. Ultra-

smooth silver surfaces with lithographically defined aberration-corrected block reflectors allow arrays of stable, high-quality-factor plasmonic cavities to be obtained. By adding a gain material, such as colloidal quantum dots, into these cavities via localized printing or simple large-area drop-casting, functional devices are created. Optical pumping at low intensities produces monochromatic SPPs matching the plasmonic cavity modes. Controlled extraction of the spaser signal followed by amplification and nanofocusing to a nearby tip, allows intense, coherent SPPs to be created. The resulting broadly-applicable spaser platform can be deployed at different wavelengths, size scales, and geometries on large-area plasmonic chips for exploiting nanoscale light-matter interactions as well as a variety of applications.

Below we discuss two different classes of electromagnetic waves that exist at a metal interface. As already introduced above, surface-plasmon polaritons (SPPs) are propagating electromagnetic waves that are bound to these interfaces. They are surface waves constrained to travel within the two dimensional space of the surface. These waves can also be confined in one or two dimensions (e.g., along a ridge or at a sharp tip, respectively) on the surface. If they are confined in two dimensions they are often referred to as localized surface plasmons. More generally, localized surface plasmons and SPPs are both referred to as types of “surface plasmons” or “plasmons.” The present invention involves creating devices that can generate surface plasmons for applications.

The spaser, which stands for “surface plasmon amplification by stimulated emission of radiation,” is a miniaturized surface plasmon analogue of a macroscopic photonic laser. Both lasers and spasers consist of the same general design: a resonator cavity provides feedback of an electromagnetic wave (photons or surface plasmons, respectively) that is amplified within a gain medium. When the gain exceeds losses in a laser, photons are directed into specific spatial and energetic modes that are defined by the spectrum of the gain medium and the geometry of the cavity. One of the cavity reflectors can then be engineered to outcouple (i.e., allow a portion of the photons to leak out of the cavity) to create an intense, coherent, monochromatic beam of light for optical applications. Analogously, a spaser allows surface plasmons to oscillate with amplification inside a plasmonic resonator cavity. If gain exceeds round-trip losses in the cavity, plasmons build up inside the resonator and can be outcoupled for useful purposes. In particular, surface plasmons allow electromagnetic energy to be focused (i.e., concentrated) into nanometer-scale spots on structured metallic films. This is useful for applications such as photonic

integrated circuits and sensors.

The first proposed spaser design used a metallic nanoparticle (as the plasmonic cavity) that was coated with a material that emitted light (also known as a film of quantum emitters). This emitting material, or gain medium, could then feed energy into the localized surface plasmon modes of the nanoparticle for amplification. The goal of such a nanoparticle spaser was to provide a source of highly-localized intense, coherent, and spectrally-narrow surface plasmons. This device would additionally benefit if it were “dark,” meaning that only surface plasmons (and not photons) were emitted from the nanoparticle. In general, surface plasmons can be dark because a momentum mismatch exists between the plasmons and photons. However, nanoscale structures such as metallic nanoparticles allow this momentum mismatch to be compensated, thus photons are also emitted from such a nanoparticle spaser. The operation of the device, and whether it is a nanoscale laser or spaser, then becomes complicated.

While this initial idea of a spaser involved metallic nanoparticles and localized surface plasmons, nearly all reports of spasers to date have operated with propagating surface plasmon polaritons (SPPs). For instance, numerous demonstrations of spasers have used semiconductor nanowires or flakes randomly placed on silver films that were first coated with a dielectric layer. Here, the edges of the gain material provide limited, but sufficient, reflection of SPPs thereby making the gain material and plasmonic cavity one and the same (R. F. Oulton, V. J. Sorger, T. Zentgraf, R. M. Ma, C. Gladden, L. Dai, G. Bartal, X. Zhang, *Nature* **461**, 629 (2009); R. M. Ma, R. F. Oulton, V. J. Sorger, G. Bartal, X. A. Zhang, *Nature Materials* **10**, 110 (2011); Y. J. Lu, J. Kim, H. Y. Chen, C. H. Wu, N. Dabidian, C. E. Sanders, C. Y. Wang, M. Y. Lu, B. H. Li, X. G. Qiu, W. H. Chang, L. J. Chen, G. Shvets, C. K. Shih, S. Gwo, *Science* **337**, 450 (2012)). These spasers can confine SPPs to sub-diffraction modal volumes within the cavity, and they are, in principle, dark devices, in which only SPPs (and not photons) are oscillating within the cavity. However, the difficulty of spatially arranging these materials on a chip-wide scale precludes their incorporation into any advanced optical or electronic circuitry (R. X. Yan, P. Pausauskie, J. X. Huang, P. D. Yang, *Proceedings of the National Academy of Sciences of the United States of America* **106**, 21045 (2009)).

Attempts to fabricate spasers via top-down methods have succeeded in accurately placing devices, but to date no devices have allowed extraction of the amplified SPPs generated within the cavity (M. T. Hill, M. Marell, E. S. P. Leong, B. Smalbrugge, Y. C. Zhu, M. H.

Sun, P. J. van Veldhoven, E. J. Geluk, F. Karouta, Y. S. Oei, R. Notzel, C. Z. Ning, M. K. Smit, *Optics Express* **17**, 11107 (2009); M. Khajavikhan, A. Simic, M. Katz, J. H. Lee, B. Slutsky, A. Mizrahi, V. Lomakin, Y. Fainman, *Nature* **482**, 204 (2012)). Still other reports have used surface plasmons within gain media but for the purpose of generating photons rather than surface-bound SPPs and therefore do not serve as on-chip analogues of lasers (N. I. Zheludev, S. L. Prosvirnin, N. Papasimakis, V. A. Fedotov, *Nature Photonics* **2**, 351 (2008)). To date, all reports of spasers remain unviable for practical on-chip implementation.

In order for a spaser to be technologically relevant, it must possess the following characteristics: (1) a high-gain medium to overcome surface-plasmon propagation losses, (2) a high quality-factor plasmonic resonator for efficient feedback, (3) above-threshold “spasing” operation under ambient conditions, (4) a means of accurately placing and orienting the device, (5) a means of directing plasmons out of the cavity, and (6) straightforward scalability to full-chip scale. With an eye on simplicity and versatility, this invention allows the systematic engineering of each component of a spaser to satisfy these design criteria. Thus, it provides a versatile platform that can serve as the foundation for advanced on-chip plasmonics.

The current invention employs a combination of top-down and bottom-up fabrication methods to independently engineer the gain material and the plasmonic resonator. More specifically, decoupling of the two structural components of the device (i.e. the gain material and the plasmonic resonator) allows one to take advantage of the accurate spatial placement and orientation of lithographically-defined plasmonic resonators with the high gain and placement flexibility of solution-processable optical gain media, such as colloidal quantum dots.

The current invention uses template stripping to fabricate high-quality metallic surfaces for plasmonic devices and circuits with integrated spasers as on-chip sources of SPPs and localized surface plasmons. Template stripping is a method to obtain ultra-smooth patterned films (P. Nagpal, N. C. Lindquist, S.-H. Oh, D. J. Norris, *Science* **325**, 594 (2009); N. C. Lindquist, P. Nagpal, A. Lesuffleur, D. J. Norris, S.-H. Oh, *Nano Letters* **10**, 1369 (2010); H. Im, S. H. Lee, N. J. Wittenberg, T. W. Johnson, N. C. Lindquist, P. Nagpal, D. J. Norris, S.-H. Oh, *ACS Nano* **5**, 6244 (2011); N. C. Lindquist, T. W. Johnson, D. J. Norris, S.-H. Oh, *Nano Letters* **11**, 3526 (2011); N. C. Lindquist, P. Nagpal, K. M. McPeak, D. J. Norris, S. H. Oh, *Reports on Progress in Physics* **75**, 036501 (2012); C. H.

- Sun, N. C. Linn, P. Jiang, *Chemistry of Materials* **19**, 4551 (2007)). Typically, a silicon surface (e.g., a silicon wafer) is first patterned using standard nanofabrication technology (e.g., electron-beam lithography, photolithography, focused-ion-beam milling, etc.). Then, a metallic film is deposited on this template and peeled off. Because the silicon template
- 5 can be prepared very precisely, and this pattern is transferred during the template-stripping process, very high quality patterned metallic films can be obtained. Several additional benefits also result. First, many copies of the same wafer-scale pattern can be easily prepared. Second, the film can be peeled off of the template right before use, protecting it from oxidation, sulfidation, or other contamination. Finally, the optical properties of the
- 10 metal can actually be improved (P. Nagpal, N. C. Lindquist, S.-H. Oh, D. J. Norris, *Science* **325**, 594 (2009); J. H. Park, P. Nagpal, S.-H. Oh, D. J. Norris, *Applied Physics Letters* **100**, 081105 (2012)) compared to that of a conventionally-deposited film. Thus, template stripping provides a simple high-throughput method for obtaining high-quality patterned metals. Although below we focus on silver as the plasmonic material, other metals such as
- 15 gold, aluminum, and copper, as well as oxides, nitrides, and alloys, can also be used (J. H. Park, P. Nagpal, K. M. McPeak, N. C. Lindquist, S.-H. Oh, D. J. Norris, *ACS Applied Materials & Interfaces* **5**, 9701 (2013)). The choice depends on the desired operational wavelength of the device as well as cost and other factors. However, to be plasmonic, the material must have a negative real component to its dielectric function.
- 20 All devices demonstrated below were operational at room temperature under air. At reduced temperatures, the decreased propagation losses in the metal and improved gain in the gain material may further improve performance. Moreover, the flexibility to use different gain media with this invention allows one to access wavelength ranges in the near-infrared where plasmonic losses are even lower. These properties indicate that this
- 25 invention allows devices to exploit intercavity effects and other phenomena in quantum plasmonics.
- More generally speaking, the present invention proposes a method of making a plasmonic device, or plasmonic chip, the method comprising the following steps:
- patterning a metallic surface;
- 30 incorporating gain material for creating coherent surface plasmon polaritons or localized surface plasmons at desired locations; and
- incorporating further elements on the surface to manipulate these surface plasmons for a desired purpose.

When talking about patterning a metallic surface, this is intending to mean the addition of structural elements, such as ridges, channels, grooves, holes, apertures, pyramids, tapers, tips, blocks, periodic arrays of the aforementioned elements, or other features that change the surface topography of an otherwise flat metallic surface. These features will typically involve changes in height away from the mean metallic surface of ~1 nanometer to several micrometers, depending on the purpose of the element. For example, a reflector for surface plasmon polaritons at a wavelength of ~630 nm should have a height of 400-1000 nm away from the flat metallic surface to ensure efficient reflection of the surface plasmon polaritons that propagate towards the reflector and strike it. The size of the structural elements in the plane of the surface can range from nanometer to micrometer in dimension. Desired locations in the second step is intending to mean that through the process of template stripping, the pattern in the metallic surface can be created through lithographic processes of the original silicon template. These patterns can be placed on this silicon template and transferred into the metallic surface. The silicon template can be patterned via optical lithography, electron-beam lithography, focused-ion-beam milling, or other silicon patterning techniques. Because silicon patterning can now be done with extreme precision, the silicon template, and hence the patterned metallic film arising from it, can contain elements that are precisely placed with respect to each other. For example, plasmonic reflectors, outcouplers, gain elements, tips, waveguides, apertures, which all involve structural elements on the metallic surface, can be placed at distances with respect to each other with ~10 nm resolution. The gain material can then be placed on and within these different structural elements as needed.

Manipulating these surface plasmons is intending to mean the addition of structural elements with precise placement relative to each other to comprise a useful plasmonic device that creates, channels, guides, focuses, transforms, or otherwise changes the properties of surface plasmon polaritons or localized surface plasmons. For the case of a spaser with an integrated amplifier and focus element, this means the addition of reflectors and gain media with the proper placement such that surface plasmons are created, directed, amplified, and focused at a nanometer-scale tip.

An additional example would be the placement of a spaser with a plasmonic waveguide channel included in the device that exhibited affinity for specific chemical or biological species that would attach when the device is exposed to these species. The output of the device would then be modified by such exposure and attachment such that the overall

device would act as a plasmonic sensing device.

According to the invention, the plasmonic circuit can be created via template stripping of a metal film from a silicon wafer.

The gain material can be incorporated at desired locations by way of at least one of the following methods: printing, drop-casting, spin-coating, evaporation, sputtering, onto a
5 desired location on the plasmonic device.

The gain material may comprise or consist of colloidal semiconductor nanocrystals or colloidal quantum dots, wherein preferably the gain material comprises or consists of Cd-based quantum dots (e.g. CdSe, CdS, or combinations thereof). Alternatively, phosphide-based (e.g. GaP, GaAs, or InP, or combinations thereof), mercury-based (e.g. HgTe, HgSe,
10 or combinations thereof), zinc-based (e.g. ZnSe or ZnS). These quantum dots can also be core/shell, core/graded-shell, or core/shell/shell quantum dots (e.g. CdSe/CdS/ZnS core/shell/shell quantum dots), where a shell of one or several materials is added successively on top of a core of a different material to optimize optical performance (e.g.
15 fluorescence efficiency, emission rate, etc.). These quantum dots can have roughly spherical shapes or can exhibit thin rectangular shapes as in semiconductor nanoplatelets (see S. Ithurria, M. D. Tessier, R. P. S. M. Lobo, B. Dubertret, Al. L. Efros, *Nature Materials* **10**, 936 (2011)).

The gain material may additionally or alternatively comprise or consist of at least one of:
20 an organic dye (e.g. a rhodamine dye), small molecules (e.g. oligothiophenes), or doped glasses (e.g. rare-earth doped garnets, such as neodymium-doped yttrium aluminum garnet),
a deposited thin film of semiconductor (with thicknesses governed by the confinement of the plasmon, preferably in the range of less than several micrometers, e.g. less than 5 or 10
25 micrometers, more preferably in the range of less than several hundred nanometers, e.g. less than 300 or 500 nm) or a two-dimensional sheet of semiconductor (e.g. GaAs),
a hybrid inorganic-organic perovskite (with the general formula $\text{CH}_3\text{NH}_3\text{PbX}_n\text{Y}_{3-n}$, where CH_3NH_3 (methylammonium) and Pb are cations, and X and Y are halide anions) or inorganic perovskite compound (e.g. CsPbX , where X is a halide anion) deposited as a
30 continuous film or film of colloidal nanocrystals (e.g. cesium lead bromide) or colloidal nanoplatelets (e.g. methylammonium lead bromide).

The gain material may further comprise or consist of one or a multitude of layers, including polymers (e.g. poly(para-phenylene vinylene) (PPV) or poly(para-phenylene)

(PPP) to provide gain, or poly(methyl methacrylate) (PMMA) or poly(lauryl methacrylate) to provide a host material into which another gain medium such as colloidal quantum dots or nanoplatelets can be embedded) or self-assembled monolayers, that are contained in a stack of different or similar layers.

- 5 The gain material may also comprise or consist of a liquid (e.g. an organic dye such as rhodamine dissolved in a solvent such as ethanol or water, or a colloidal nanomaterial such as CdSe/CdS/ZnS core/shell/shell quantum dots dispersed in an hydrophobic organic solvent such as hexane, toluene, or chloroform).

The invention further proposes a method of creating a source of coherent and
10 monochromatic surface plasmon polaritons or localized surface plasmons within an integrated plasmonic circuit, the method comprising the following steps:

creating a plasmonic resonator cavity with well defined mode characteristics;

pumping a gain material inside this cavity;

- and generating a plasmonic signal that can be out-coupled to neighboring plasmonic,
15 photonic, or electronic elements on the device.

Well-defined mode characteristics is intending to mean that the plasmonic cavity can be designed to output plasmons (analogously to the design of laser cavities for photons) with specific optical properties, such as its central wavelength, linewidth, spatial profile, direction, and intensity.

- 20 At least a portion of the one or more surface features that define the device may comprise a block reflector, wherein preferably the block reflectors are designed to be aberration corrected to create high-quality-factor stable plasmonic resonators.

The gain material can be used to amplify the plasmonic signal.

The gain material can be chosen as detailed above.

- 25 The device can be operated at ambient temperature and in air or can be operated at reduced temperature and/or under inert gas or vacuum. Reduced temperature is intending to mean that the device is cooled below room temperature (e.g. with a thermoelectric cooler to below zero degrees Celsius, or with cryogenic cooling to 77 Kelvin or below 10 Kelvin) to improve specific performance aspects of the device (e.g. to narrow the spectral linewidth
30 decrease the spasing threshold, or to improve sensing characterisitics).

The gain material can be pumped optically and/or electrically. Optical pumping can be achieved by shining light on the gain material from above (e.g. with a laser or light-emitting diode). Electrically pumping can be achieved by injecting electrical carriers

(electrons and holes) into the gain material from integrated electrodes. As plasmonic structures inherently contain metallic elements, typically made from highly conductive metals such as silver and gold, such electrodes can be easily incorporated into the device design.

5 Further the invention relates to a device, preferably made using a method according to any of the preceding claims comprising:

a metal film comprising one or more distributed surface structural features (such as ridges, channels, grooves, holes, apertures, pyramids, tapers, tips, blocks, periodic arrays of the
10 otherwise flat metallic surface) configured to create a source of coherent monochromatic surface plasmon polaritons or localized surface plasmons that provide a plasmonic signal.

The device can be a plasmonic laser or spaser that can be incorporated into a larger plasmonic device and/or a plasmonic amplifier that can be incorporated into a larger plasmonic device results.

15 The output of the plasmonic laser or spaser can be amplified and/or the plasmonic signal can be focused to a specific location on the device. The plasmonic signal of the device can be used to sense. The plasmonic signal can also be used within an integrated plasmonic circuit. The plasmonic signal can also be used within a microfluidic channel.

Further embodiments of the invention are laid down in the dependent claims.

20

BRIEF DESCRIPTION OF THE DRAWINGS

Preferred embodiments of the invention are described in the following with reference to the drawings, which are incorporated in and constitute a part of this disclosure, illustrate several aspects of the present invention and together with description of the exemplary
25 embodiments serve to explain the principles of the present invention. In the drawings,

Fig. 1 shows a scanning electron micrograph of a plasmonic cavity consisting of two ~600-nm-tall block reflectors coming out of an ultra-smooth silver surface; the surface plasmon polaritons oscillate along the surface of the metal between the reflectors; the curvature of the reflectors is designed to
30 create a stable plasmonic cavity;

Fig. 2 shows a scanning electron micrograph of a thin film of colloidal quantum dots (dark stripe between the reflectors) that was printed within the plasmonic cavity; this stripe acts as the gain material to amplify the SPPs

that are oscillating between the curved reflectors;

Fig. 3 shows a scanning electron micrograph of an array of spasers placed by design on an ultra-smooth silver surface; the six devices in the first two columns on the left of the micrograph have stripes of colloidal quantum dots that were printed into them; the rightmost column of devices remain empty;

Fig. 4 shows the reflectors of the plasmonic resonators which are aberration-corrected reflectors with a radius-of-curvature equal to the separation between the reflectors ($R=2L$ cavity); SPPs emitted within the cavity are spatially confined within a stable plasmonic cavity mode (shown in red);

Fig. 5 a scattering spectrum (solid curve) for ~ 100 colloidal quantum dots (see spot in the cartoon inset) placed within the plasmonic cavity; when the quantum dots are photoexcited by blue light (see solid downward arrow in the cartoon inset) they generate SPPs in the plasmonic modes defined by the cavity; the spectrum measured by detecting SPPs scattered into photons at the outer reflector of one of the reflectors (see red arrow in the cartoon inset) is shown as the red curve; the calculated plasmonic modes are in grey;

Fig. 6 shows a scanning electron micrograph of a thin film of colloidal quantum dots (dark stripe between the reflectors) that was printed within the plasmonic cavity; the stripe dimensions were chosen to maximize the spatial overlap with the plasmonic cavity mode (see Fig. 4); this stripe acts as the gain material to amplify the SPPs that are oscillating between the curved reflectors;

Fig. 7 shows the situation when the plasmonic cavity is filled with CQDs (see horizontal film depicted in the cartoon inset), the scattered SPP emission (measured as in Fig. 5) is modulated by the plasmonic modes of the resonator on the less absorptive low-energy side of the spectrum; the measured scattering spectrum is shown as the red curve; the calculated plasmonic modes are shown in grey;

Fig. 8 shows how under pulsed excitation at an intensity of $130 \mu\text{J}/\text{cm}^2$, a small peak rises on top of the scattering spectrum where a plasmonic mode is calculated to be; right inset: the real-space image from the CQD stripe; the excitation light was rejected by optical filtering); the bright spots at the left and right of the stripe represent scattering of photons from the reflectors;

- Fig. 9 shows how at higher pump power density, $250 \mu\text{J}/\text{cm}^2$, the small peak in Fig. 8 narrows and increases in intensity; right inset shows a real-space image of the device, as in Fig. 8; the CQD stripe exhibits decreased emission in the middle of the cavity with increased signal at the edges; the spectrum and the image are a clear sign of the onset of spasing;
- 5 Fig. 10 shows the scattering spectra, as shown in Figs. 8-9, for plasmonic cavities filled with CQDs emitting at three different wavelengths (602, 625, and 633 nm, left to right columns); for each column, the scattering spectra, detected from the outer edge of the block reflector, are shown as a function of the pump intensity; in all cases, spectrally narrow plasmonic modes appear
- 10 above a threshold pumping intensity;
- Fig. 11 shows the scattering spectrum (solid curve) of the spasing device from the middle of the right column in Fig. 10; the pump intensity is $225 \mu\text{J}/\text{cm}^2$; a single plasmonic mode is apparent; such spasing peaks have linewidths that
- 15 are typically on the order of 2 meV (0.65 nm); the dotted line depicts the measured emission (photoluminescence) spectrum from a film of colloidal quantum dots on a flat silver surface;
- Fig. 12 shows the input-output power plot of a spaser device; the devices exhibit low pump thresholds (as low as $\sim 100 \mu\text{J}/\text{cm}^2$) for spasing;
- 20 Fig 13 shows how at very high pump powers, the CQD-filled spaser devices start to emit SPPs over a larger energy range than expected from the biexciton (X/BX) gain of the colloidal quantum dots; see solid curve for the measured scattering spectrum of the device; the spasing peaks near 590 nm indicate that multiexcitons are providing sufficient gain to overcome plasmonic
- 25 losses at shorter wavelengths; thus, many plasmonic cavity modes can be mapped out by the spasing peaks within the envelopes of the biexciton- and multiexcitons-gain curves; the periodic peaks shown in grey are calculated plasmonic modes, assuming a refractive index for the quantum-dot film of 1.6; the broad dashed peak (centered around ~ 630 nm) represents the measured emission (photoluminescence) spectrum from a film of colloidal
- 30 quantum dots on a flat silver surface;
- Fig. 14 shows the measured free spectral range (FSR) of the spasing peaks obtained from 41 fabricated devices; the FSR matches the expected spacing for

plasmonic, as opposed to photonic, modes;

Fig. 15 shows a scanning electron micrograph of a spaser in which one of the reflectors has been elongated to waveguide the SPP signal and focus it to a nanoscale tip. Colloidal quantum dots have been printed as a stripe between the reflectors;

Fig. 16 shows a real-space image (false coloring) of the device shown in Fig. 15; the images demonstrate that above threshold, the spaser signal is indeed waveguided along the elongated reflector and focused to a tip; the reflector outline is indicated as a visual aid in the right-hand side of the figure; the intensity scale is enhanced to the right of the vertical dashed line to see the plasmonic signal scattered from the tip;

Fig. 17 shows a real-space image (false coloring) of a device similar to the one shown in Fig. 15; however, instead of printing the colloidal quantum dots in the cavity, they are drop-casted over the entire device; the image here shows the emission from the device when optically pumped below the spasing threshold;

Fig. 18 shows a real-space image (false coloring) of the same device shown in Fig. 17, but now pumped above the spasing threshold; the output from the spasing cavity is further amplified as it travels to the tip; indeed, the image here is 100 times more intense than the image shown in Fig. 17;

Fig. 19 shows a scanning electron micrograph of a “bike wheel” structure containing 12 spasers with elongated tip reflectors directed toward a central point; this device demonstrates that more complicated structures with various integrated components can be easily fabricated;

Fig. 20 shows a real-space image (false coloring) of the device shown in Fig. 19, after drop casting colloidal quantum dots on the entire device; the image on the left half is obtained with optical pumping below the spasing threshold; the image on the right half is obtained with optical pumping above the spasing threshold; the signal in the right image is 200 times more intense and shows interference fringes, indicating coherence in the output of the spasers.

DESCRIPTION OF PREFERRED EMBODIMENTS

The exemplary embodiments of the present invention described herein are not intended to be exhaustive or to limit the present invention to the precise forms disclosed in the following detailed description. Rather the exemplary embodiments described herein are chosen and described so those skilled in the art can appreciate and understand the principles and practices of the present invention.

Example 1

In this exemplary embodiment of the present invention, appropriate substrates must first be fabricated. High quality Si wafers are readily available from commercial sources. For electronic applications, crystalline silicon is grown as long cylindrical boules of various diameters. These boules are then sliced and polished to yield wafers in several standard orientations.

The first step to produce a device is to implant the pattern of our resonators onto the (100) surface of silicon wafers with electron-beam lithography and reactive ion etching. Following thermal evaporation of silver, the plasmonic metal that offers the highest figure of merit for SPPs in the visible and near-infrared (K. M. McPeak, S. V. Jayanti, S. J. P. Kress, S. Meyer, S. Iotti, A. Rossinelli, D. J. Norris, *ACS Photonics* **2**, 326 (2015)), we strip the Ag film from the Si template (P. Nagpal, N. C. Lindquist, S. H. Oh, D. J. Norris, *Science* **325**, 594 (2009)) to produce ultra-smooth planar Ag surfaces with incorporated ~600-nm-tall block reflectors with walls normal to the surface (Fig. 1). These block reflectors possess high reflectivity (>90% according to simulation) for impinging SPPs. This is necessary to obtain high-quality-factor plasmonic resonators (G. Brucoli, L. Martin-Moreno, *Physical Review B* **83**, 075433 (2011); S. J. P. Kress, F. V. Antolinez, P. Richner, S. V. Jayanti, D. K. Kim, F. Prins, A. Riedinger, M. P. C. Fischer, S. Meyer, K. M. McPeak, D. Poulidakos, D. J. Norris, *Nano Letters* **15**, 6267 (2015)).

The second step is to add a gain material to this resonator. In this embodiment, chemically-synthesized colloidal CdSe/CdS/ZnS core/shell/shell quantum dots (CQDs) are selected for the gain medium because they have high emission quantum yields (often >90%), have large absorption and emission transition dipoles, are photostable, and can be packed at high densities without the self-quenching effects commonly observed in organic dyes. Furthermore, as particles in a liquid dispersion, CQDs can be reproducibly placed with near-nanometer accuracy using electrohydrodynamic NanoDrip (P. Galliker, J. Schneider, H. Eghlidi, S. Kress, V. Sandoghdar, D. Poulidakos, *Nature Communications* **3**, 890 (2012); S. J. P. Kress, P. Richner, S. V. Jayanti, P. Galliker, D. K. Kim, D. Poulidakos, D.

J. Norris, *Nano Letters* **14**, 5827 (2014)).

With this printing technique, one can place well-defined densely packed CQD stripes directly onto the planar silver surface between the reflector walls. Figure 2 highlights the pristine walls of the block reflectors and the accurate placement of dense CQD stripes for a functional device. Because of the placement precision and accuracy of both electron-beam lithography and NanoDrip printing, these devices can be arbitrarily designed and positioned, as shown in Fig. 3.

In conventional macroscopic laser cavities, stable lasing modes are supported between aberration-corrected concave mirrors. Analogously, one can design plasmonic reflectors with a parabolic correction to produce resonators supporting stable, well-defined plasmonic cavity modes. Experiments revealed that the highest-performing plasmonic resonators at ~ 630 nm consisted of reflectors spaced $10\text{ }\mu\text{m}$ apart with a radius-of-curvature at their apex equal to twice their spacing ($R=2L$ cavity). The resulting stable and aberration-corrected plasmonic mode, calculated using a simple ray-tracing and reflection algorithm (see Methods), is highlighted in red in Fig. 4.

One can characterize the quality of such plasmonic cavities by first printing ~ 100 CQDs into the center of the resonator. The SPPs generated by the CQDs (which are optically excited, or “pumped”) can be measured by observing the scattered emission at the outer edge of the reflector walls (Fig. 5). As in the case of plasmonic wedge-waveguide resonators (S. J. P. Kress, F. V. Antolinez, P. Richner, S. V. Jayanti, D. K. Kim, F. Prins, A. Riedinger, M. P. C. Fischer, S. Meyer, K. M. McPeak, D. Poulikakos, D. J. Norris, *Nano Letters* **15**, 6267 (2015)), the standard photoluminescence spectrum of the CQDs (Fig. 5, red curve) is strongly modified in the cavity, as shown by the calculated plasmonic resonator modes (Fig. 5, dotted lines). The linewidth of the modified spectrum can be as narrow as 1.6 nm (1.8 meV), indicating a plasmonic cavity with a quality factor Q of 400.

In order for the printed CQDs to provide maximum SPP gain, they must be printed with maximum spatial overlap with the plasmonic cavity mode. Since our calculations suggest a cavity beam waist of $\sim 1\text{ }\mu\text{m}$ (Fig. 4), we printed stripes of CQDs of $2\text{ }\mu\text{m}$ width to ensure lateral overlap with SPPs (Fig. 6). For CQD films of sufficient thickness ($>100\text{ nm}$), low-intensity LED illumination yields scattered SPP spectra as shown in Fig. 7 (red curve). Here, modification of the spectrum is only apparent on the low-energy side due to increasing absorption at higher energy due to the CQDs. Additionally, compared to Fig. 5, the ripples in the spectrum have closer spacing, as expected from calculated cavity modes

(Fig. 7, dotted lines) that account for the increased refractive index of the CQD stripe relative to air.

Under more intense pulsed optical excitation of the CQDs, the scattered SPP spectrum and the spatial distribution of the measured signal change dramatically. In Fig. 8, the scattered
5 SPP spectrum at a pump power density of $130 \mu\text{J}/\text{cm}^2$ is shown. Here, the ripples on the low-energy side of the spectrum have become slightly attenuated and a small peak has formed at the top of the spectrum. At this wavelength a plasmonic cavity mode is calculated to exist. As the pump power is raised further, this small peak becomes sharper and more intense (Fig. 9). The insets on the right-hand sides of Figs. 8 and 9 show the real-
10 space images of the resonators (false coloring). (The excitation light is rejected from these images via optical filtering.) As the pump power increases, the spatial distribution of the scattered-light intensity shifts dramatically. The relative intensity along the center of the CQD stripe greatly diminishes relative to the edges. This is a sign that SPPs are undergoing
15 stimulated emission, therefore depleting the photoluminescence from the CQDs in the center of the cavity and resulting in increased scattering of SPPs into photons at the reflectors (due to less than 100% reflection). The changes in both the spectral and spatial distribution of scattered SPPs with increasing pump power confirm the stimulated emission and amplification of SPPs into a single plasmonic mode defined by the resonator. In other
words, these data demonstrate the onset of spasing.

20 Because the emission energy of the CQDs can be tuned by changing the size of these semiconductor nanoparticles, the wavelength of the output from the device can be varied by printing different CQDs into the resonators. Figure 10 shows the scattered SPP spectra measured from three different sizes of CQDs inserted into the plasmonic resonators. For the 602-nm- and 625-nm-emitting CQD samples, two spasing modes change in relative
25 intensity for different pump powers. This mode competition, also observed in other micro- and macro-lasers, occurs as certain modes are preferentially amplified depending on slight changes in the cavity conditions.

The spasing can be further characterized by focusing on the devices with 633-nm-emitting CQDs. As shown in Fig. 11, the spasing mode is narrow with a typical linewidth of ~ 2
30 meV (0.65 nm). In Fig. 12, the total output power is plotted as a function of the pump power for the device in Fig. 10. The output power has a noticeable inflection point with increasing pump power at $\sim 180 \mu\text{J}/\text{cm}^2$. Thresholds have been measured in devices as low as $100 \mu\text{J}/\text{cm}^2$. These thresholds are surprisingly small given that the best reported CQD

lasers, which presumably have much less loss than spasers, have pump thresholds that are nearly the same. Lower thresholds can be expected for spasers and plasmonic lasers because of Purcell enhancement (E. M. Purcell, *Physical Review* **69**, 681 (1946)) of the radiative lifetime and high spontaneous-emission coupling factors β . Higher β factors result in lower spasing thresholds because as excitons in the CQDs are more efficiently coupled to plasmonic modes, more SPPs can be stimulated and amplified. Another contributing factor may be the fact that Ag is a good thermal conductor and it has been shown that heating in CQD lasers have a profound impact on their lasing thresholds (M. M. Adachi, F. J. Fan, D. P. Sellan, S. Hoogland, O. Voznyy, A. J. Houtepen, K. D. Parrish, P. Kanjanaboos, J. A. Malen, E. H. Sargent, *Nature Communications* **6**, 8694 (2015)).

At very high pump powers, changes in the spectra are observed that are unique to semiconductor quantum dots (CQDs). CQDs typically provide gain through relaxation of biexcitons (BX). However, at high pump excitation, more than two excitons can be excited in each CQD. In this case, energy is released from so-called multiexciton states (MX). As seen in Fig. 13, even these higher-energy multiexcitons (around 590 nm) can couple into the spasing modes. These multiexcitons indeed have significantly higher gain than their biexciton counterparts (emitting around 630 nm). This higher gain due to the multiexcitons is enough to overcome the higher propagation losses at these shorter wavelengths. Moreover, the spasing modal structure (see Fig. 13) is clearly revealed in the spectral envelopes corresponding to the biexciton and multiexcitons regions of the CQD spectrum, in perfect agreement with the predicted spasing modes (Fig. 13, dotted lines).

The theoretical spasing modes in Fig. 13 were calculated based on a CQD film of refractive index $n = 1.60$. This is slightly less than the value measured from similar films of these CQDs via ellipsometry ($n = 1.75$). However, this decrease in n is in line with the blueshift in the spasing mode at higher pump powers. Such a blue shift corresponds to a decrease in the real part of the dielectric function, as observed in other semiconductors. In other words, the refractive index of the optically pumped film of CQD decreases due to the significant exciton population.

When one measures the peak separation between spasing peaks slightly above the spasing threshold, one can quantitatively determine that these peaks indeed arise from plasmonic modes. In Fig. 14, we plot a histogram of the free-spectral-range (FSR) values for 41 different resonators filled with either 625-nm- or 635-nm-emitting CQDs. For this plot only high-intensity peaks with spacings greater than 10 meV were considered. One can

then compare these to the free spectral ranges expected for the fundamental photonic TE mode and the fundamental plasmonic TM mode in a film of refractive index 1.65 to 1.75 with thicknesses ranging from 110 to 400 nm. These values approximate the range of values expected for the CQD stripes in these devices. Note that the printed stripes are likely to be slightly less ordered than drop-cast CQD films because of the NanoDrip deposition process. The calculations show that the free spectral range values overwhelmingly coincide with the plasmonic modes of the cavity, indicating true spasing action.

In order for such devices to be technologically relevant, one also requires the ability to extract propagating SPPs from the cavity in a controlled manner. Figure 5 and Figs. 7-10 already show that the spectra of SPPs inside the cavity can be measured when the SPPs travel over the block reflectors and scatter off their outer edge. One can further exploit this by extending the reflector and using it as a plasmonic waveguide. As shown in Fig. 15, one can create a reflector of length $\sim 35 \mu\text{m}$ with a taper angle of 5.75 degrees to demonstrate not only plasmonic waveguiding, but also nanofocusing of the SPPs generated by the cavity.

The optical image of the same device pumped above the spasing threshold is shown in Fig. 16. The image is split into two portions with different contrast settings. On the left of the vertical dashed line, one can clearly see that the device is above threshold as the inside of the stripe is nearly dark due to SPP stimulated emission. On the right of the vertical dashed line, we can see that SPPs are guided and focused to the tip where SPP outscattering can then be detected. The spectrum measured at the tip shows that is is clearly due to the spasing mode. Despite the controlled extraction of SPPs, this arrangement would benefit further from additional amplification of the coherent output of the spaser before focusing it to a nanoscale tip.

In the present invention, additional amplification can be easily incorporated by adding more gain material to the relevant path of the SPPs. In this case, the output of the spaser will be increased as it passes across the structure with additional gain material.

30 Example 2

In this second exemplary embodiment of the present invention, a drop-casting method is used to deposit the gain material (instead of a printing method). Simple placement of a liquid droplet that contains the CQDs onto the metallic surface with the spaser cavities

(and related structures), allows the gain material to be added both to the plasmonic cavities as well as the surrounding structures (*e.g.*, on the top of the reflectors). As the liquid dries, the quantum dots deposit as a film over the entire integrated device. The size of the droplet can also be controlled to place the CQDs within a selected area of a given size. Further, the shape of the liquid meniscus can be used to control where the CQDs are placed.

Drop-casting could be achieved by the following steps. First, a template-stripped substrate (*e.g.*, ~ 2.5 cm x 2.5 cm in area) that contained the silver plasmonic resonators and other structures was prepared. Second, this substrate was placed onto a cooling block held at 5 degrees Celsius within a nitrogen environment. Third, colloidal quantum dots dispersed in hexane were dispensed through a micropipette tip onto the surface and allowed to dry. The CQDs dried into uniform thin films that filled the resonator cavities and other structures over nearly the entire surface of the substrate.

As an example of the output of this approach, Figs. 17-18 show optical images of a plasmonic resonator with the same structure as in Figs. 15-16. However, in the structure in Figs. 17-18, the CQDs were drop-casted over the entire device. When such devices are optically pumped, the optical images can be compared below (Fig. 17) and above (Fig. 18) the spasing threshold. In Fig. 17, one can see that while the tip is bright, the distribution of photoluminescence around the resonators is fairly uniform. Above threshold, in Fig. 18, the spatial distribution completely changes. Most of the signal comes from the edges of the elongated reflector and its tip. In fact, the intensity increases at further distances from the cavity – a clear sign of SPP amplification. We highlight that the number of pump pulses needed to produce Fig. 18 is 100-fold less than Fig. 17. A cross-section of the intensity increase along the ridges of the tip reflector suggest a modal gain of ~ 100 cm⁻¹ which implies a material gain exceeding 1000 cm⁻¹. This results in highly concentrated SPPs at sharp tips.

Example 3

Of course, due to the flexibility of this invention, one can design many circuits containing spasers as SPP sources. Additional amplification can be added to these structures as needed. To provide an example of a more sophisticated structure that is possible with this invention, Fig. 19 shows a “bicycle wheel” structure with the tips of each “spoke” pointed towards a common center. Optical images obtained at pump intensities below and above the spasing threshold are shown on the left and right of Fig. 20, respectively. Below

threshold, the intensity is uniform throughout with slightly higher intensity near the center. Above threshold, the spasing signal is amplified along the tip reflector as in Fig. 18. The appearance of interference fringes that appear as “tree rings” in the structure are a clear indication of the coherent nature of the SPPs generated by the device.

- 5 While this represents an example of a more complicated device that can be created with this invention, the parameter space available is vast due to the versatility of this platform. For instance, different types of resonators and waveguides can be fabricated simply by changing the shape of the reflector walls. Devices can also be made that are significantly smaller than those presented here if different reflector designs are employed. With
10 generation and amplification of spaser signals, many plasmonic elements for circuits become available for applications.

Example 4

- The examples above have focused on colloidal quantum dots as a versatile gain material
15 that can be deposited by printing or simple drop-casting. In other words, this invention has taken advantage of the fact that this material is solution processable. However, many other solution processable gain media are available, including organic dyes, organic molecules, rare-earth doped solids, phosphors, hybrid organic-inorganic perovskites, *etc.* For example semiconductor nanoplatelets (C. She, I. Fedin, D. S. Dolzhenkov, A. Demortière, R. D.
20 Schaller, M. Pelton, D. V. Talapin, *Nano Letters* **14**, 2772 (2014)) or perovskites (B. R. Sutherland, E. H. Sargent, *Nature Photonics* **10**, 295 (2016)) could be utilized. Alternatively, a thin film of a semiconductor gain medium could be deposited on the plasmonic structure (either over the entire structure or on a selected part) to provide gain. Another option is to laminate two-dimensional sheets (e.g. MoS₂) of gain material onto the
25 structure. Gain materials can also be pre-mixed with polymers before deposited via spin-coating or drop casting. Finally, the gain material can be deposited as one of multiple layers that are placed on the plasmonic structure. This allows the gain media to be placed at an ideal separation distance, which may be important for device operation, depending on the design.

30

Example 5

While here, for simplicity, optical excitation has been used to pump the gain material, it is well known to those skilled in the art, that gain media in lasers and spasers can also be

electrically pumped. Thus, further embodiments of this invention involve incorporation of electrical injection layers to excite the gain material at the appropriate location. As the plasmonic structures are typically conductive, the plasmonic device itself can serve as an electrical path to carry current to the gain medium.

- 5 The present invention has now been described with reference to several exemplary embodiments thereof. The entire disclosure of any patent or patent application identified herein is hereby incorporated by reference for all purposes. The foregoing disclosure has been provided for clarity of understanding by those skilled in the art. No unnecessary limitations should be taken from the foregoing disclosure. It will be apparent to those
- 10 skilled in the art that changes can be made in the exemplary embodiments described herein without departing from the scope of the present invention. Thus, the scope of the present invention should not be limited to the exemplary structures and methods described herein, but only by the structures and methods described by the language of the claims and the equivalents of those claimed structures and methods.

CLAIMS

1. A method of making a plasmonic device, or plasmonic chip, the method comprising the following steps:
patterning a metallic surface;
incorporating gain material for creating coherent surface plasmon polaritons or localized surface plasmons at desired locations; and
incorporating further elements on the surface to manipulate these surface plasmons for a desired purpose.
2. The method of claim 1, wherein the plasmonic circuit is created via template stripping of a metal film from a silicon wafer.
3. The method according to any preceding claim, wherein the gain material is incorporated at desired locations by way of at least one of the following methods: printing, drop-casting, spin-coating, evaporation, sputtering, onto a desired location on the plasmonic device.
4. The method according to any preceding claim, wherein the gain material comprises or consists of colloidal semiconductor nanocrystals or colloidal semiconductor quantum dots of shapes including nanoplatelets, wherein preferably the gain material comprises or consists of Cd-, Hg-, In-, Ga-, Sn-, Zn-, or Ag-based quantum dots or core/shell, core/grade-shell, or core/shell/shell quantum-dot or nanoplatelet structures, such as CdSe based quantum dots, optionally containing combinations of Cd-, Hg-, In-, Ga-, Sn-, Zn-, or Ag-based semiconductors.
5. The method according to any preceding claim, wherein the gain material comprises or consists of at least one of:
an organic dye, small molecules, or rare-earth-doped inorganic glass or solid matrix,
a deposited thin film of semiconductor or a two-dimensional sheet of semiconductor,

an inorganic perovskite or hybrid inorganic-organic perovskite compound, as a continuous film or film of colloidal nanocrystals, colloidal nanoplatelets.

6. The method according to any preceding claim, wherein the gain material comprises or consists of one or a multitude of layers, including polymers or self-assembled monolayers, that are contained in a stack of different or similar layers.
7. The method according to any preceding claim, wherein the gain material comprises or consists of a liquid.
8. A method of creating a source of coherent and monochromatic surface plasmon polaritons or localized surface plasmons within an integrated plasmonic circuit, the method comprising the following steps:
creating a plasmonic resonator with well defined mode characteristics;
pumping a gain material inside this cavity;
and generating a plasmonic signal that can be out-coupled to neighboring plasmonic, photonic, or electronic elements on the device.
9. The method of claim 8, wherein at least a portion of the one or more surface features that define the device comprises a block reflector, wherein preferably the block reflectors are designed to be aberration corrected to create high-quality-factor stable plasmonic resonators.
10. The method of any of claims 8-9, wherein the gain material is used to amplify the plasmonic signal.
11. The method of any of claims 8-10, wherein the device is operated at ambient temperature and in air
and/or is operated at reduced temperature and/or under inert gas or vacuum.
12. The method of any of claims 8-11, wherein the gain material is pumped optically and/or electrically.

13. A device, preferably made using a method according to any of the preceding claims comprising:
a metal film comprising one or more distributed surface features configured to create a source of coherent monochromatic surface plasmon polaritons or localized surface plasmons that provide a plasmonic signal.
14. The device of claim 13, wherein a plasmonic laser or spaser that can be incorporated into a larger plasmonic device and/or a plasmonic amplifier that can be incorporated into a larger plasmonic device results.
15. The device of claim 13 or 14, wherein the output of the plasmonic laser or spaser is amplified and/or wherein the plasmonic signal is focused to a specific location on the device.
16. The device of any of claims 13 - 15, wherein the plasmonic signal is used to sense.
17. The device of any of claims 13 - 16, wherein the plasmonic signal is used within an integrated plasmonic circuit.
18. The device of any of claims 13 - 17, wherein the plasmonic signal is used within a microfluidic channel.

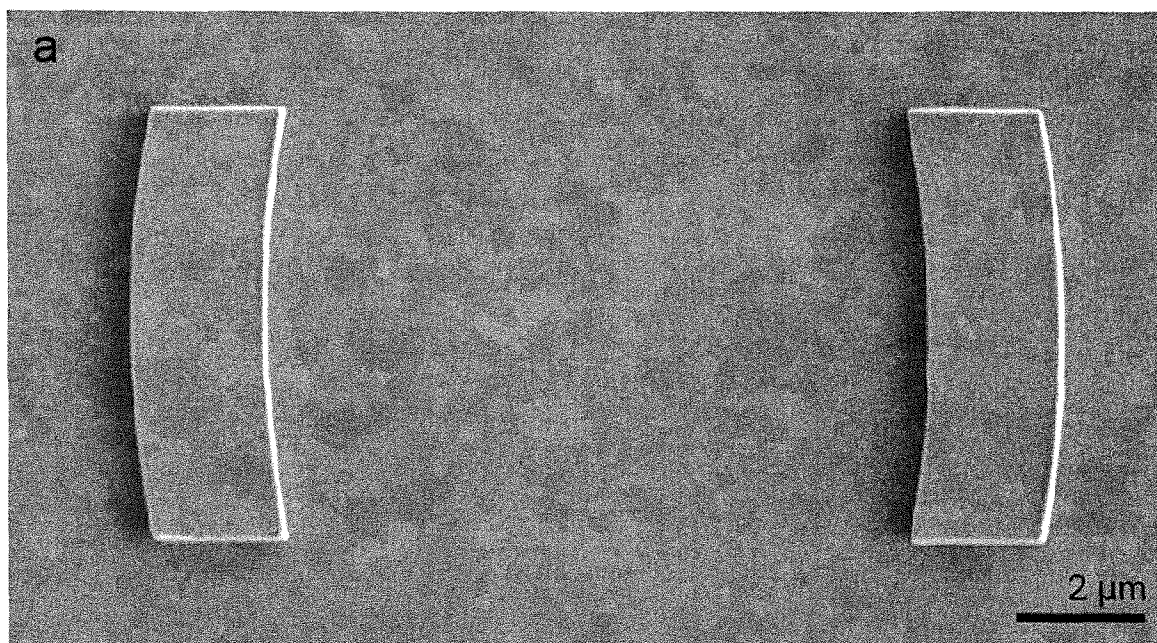


FIG. 1

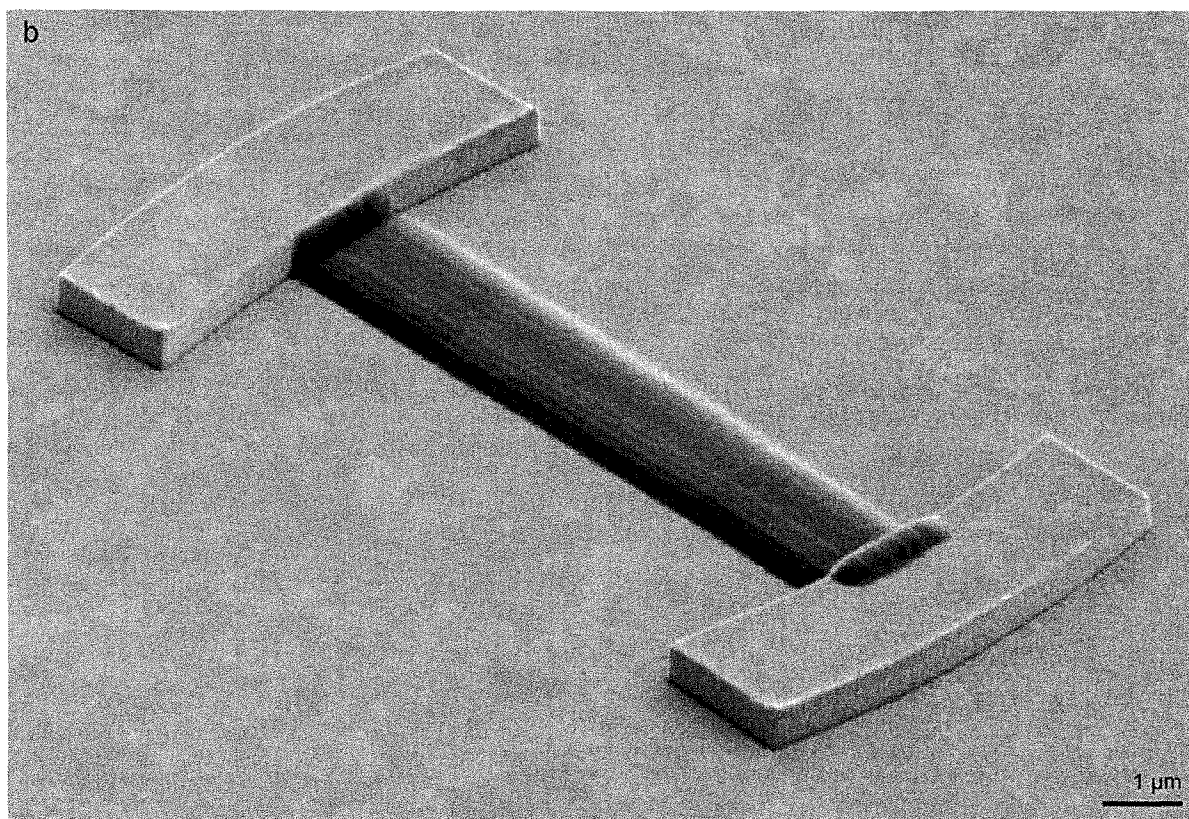
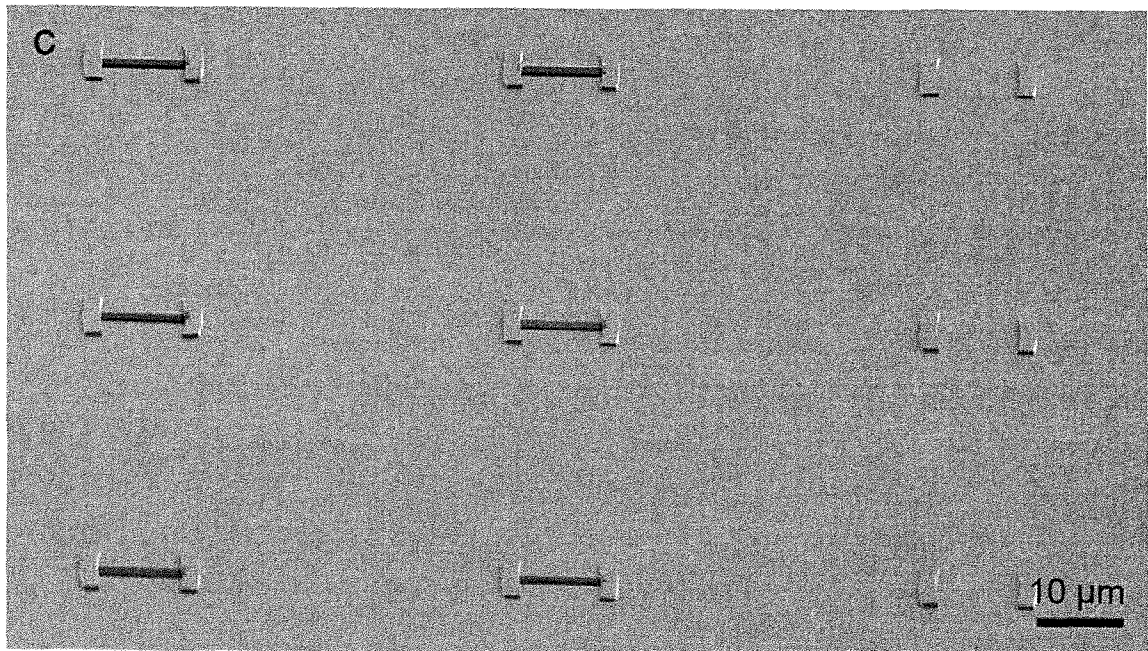
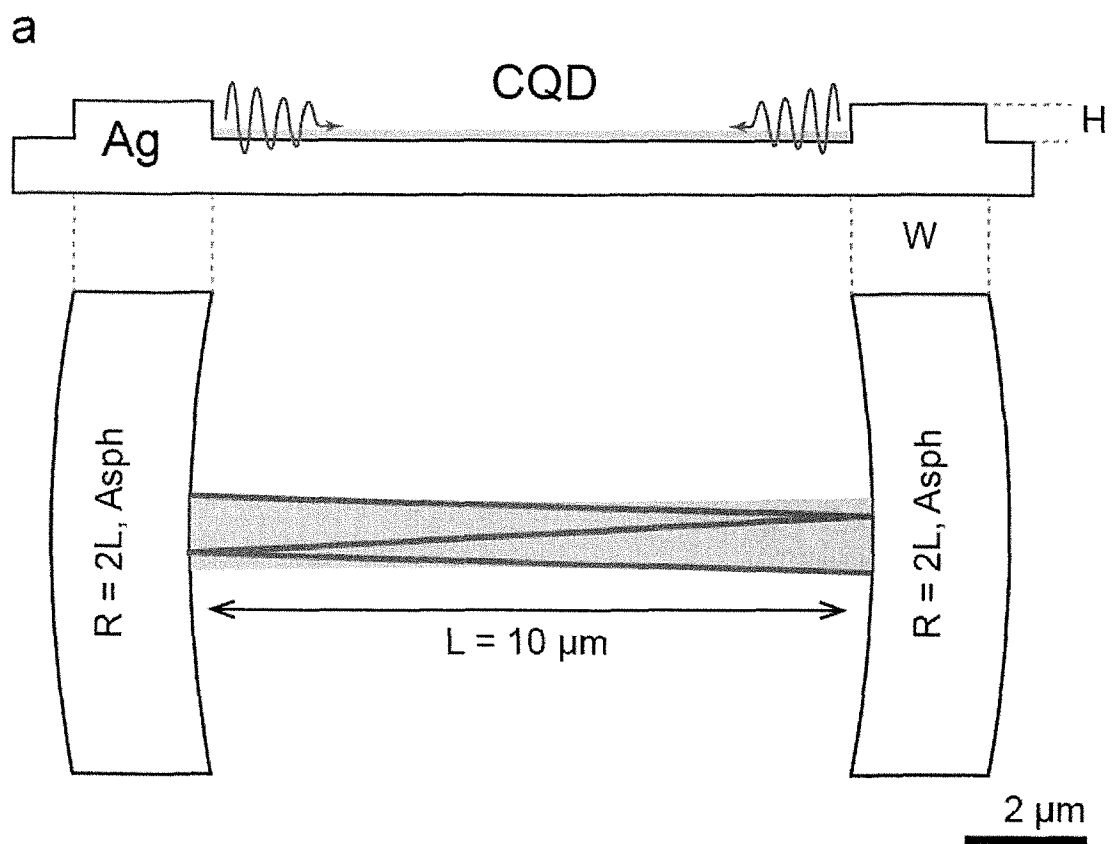
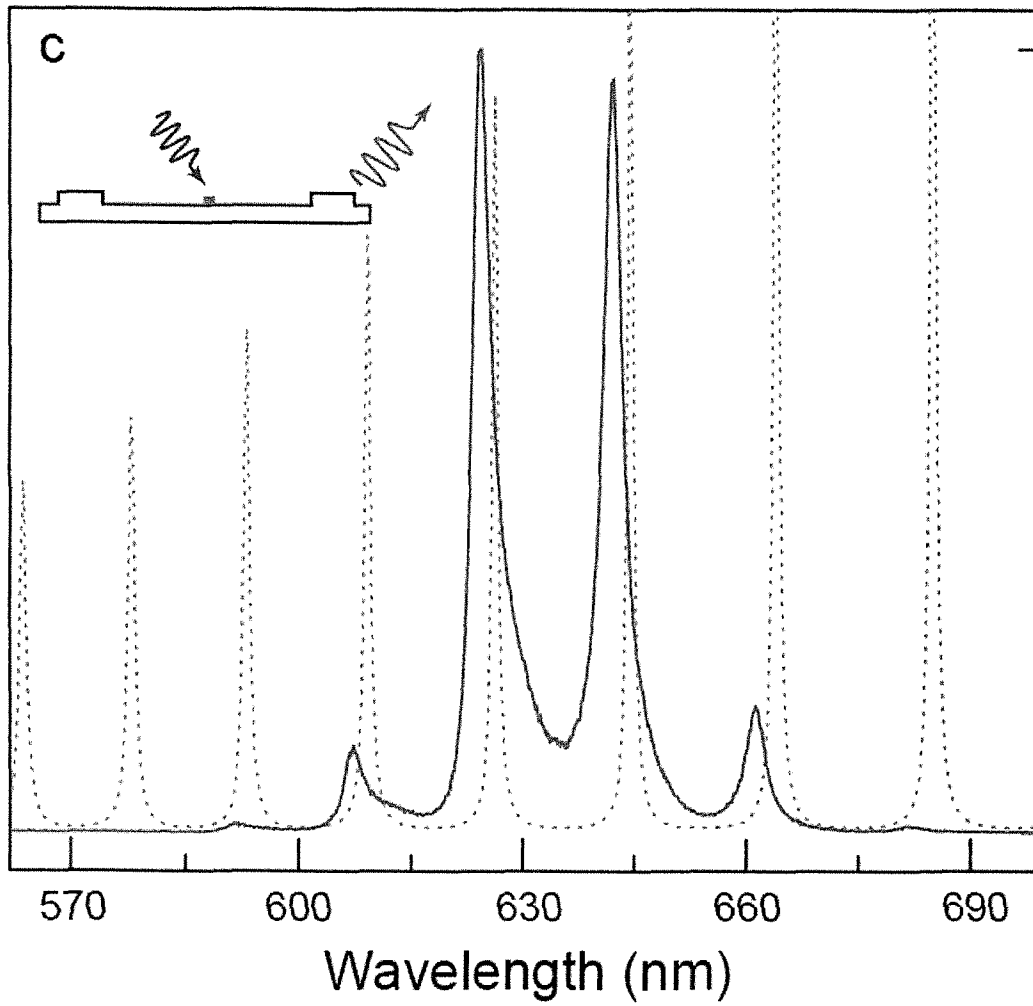
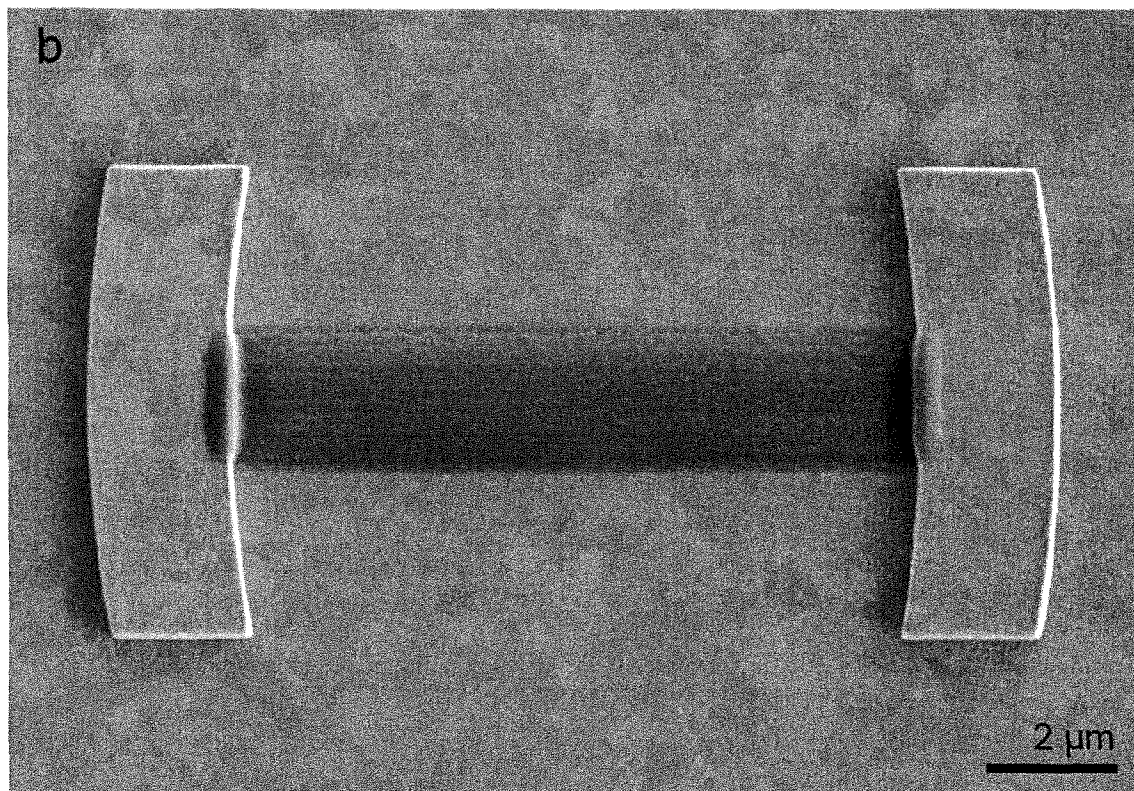
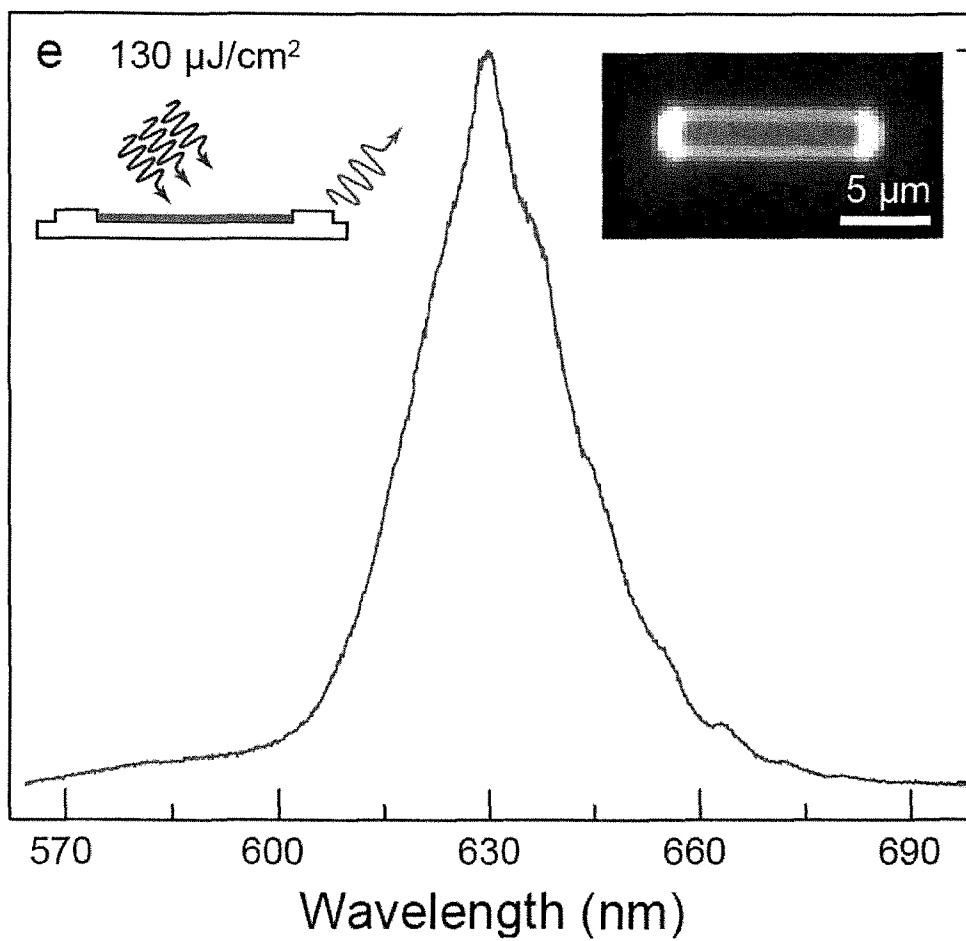
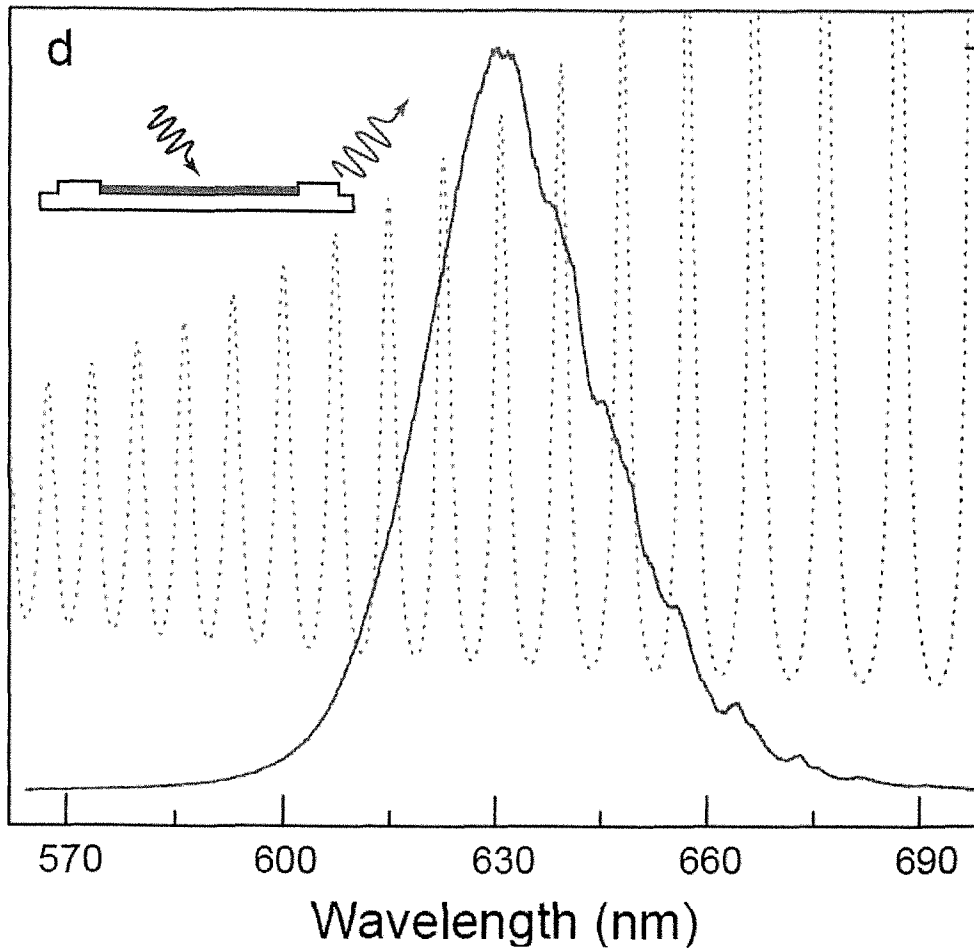


FIG. 2

**FIG. 3****FIG. 4**

**FIG. 5****FIG. 6**

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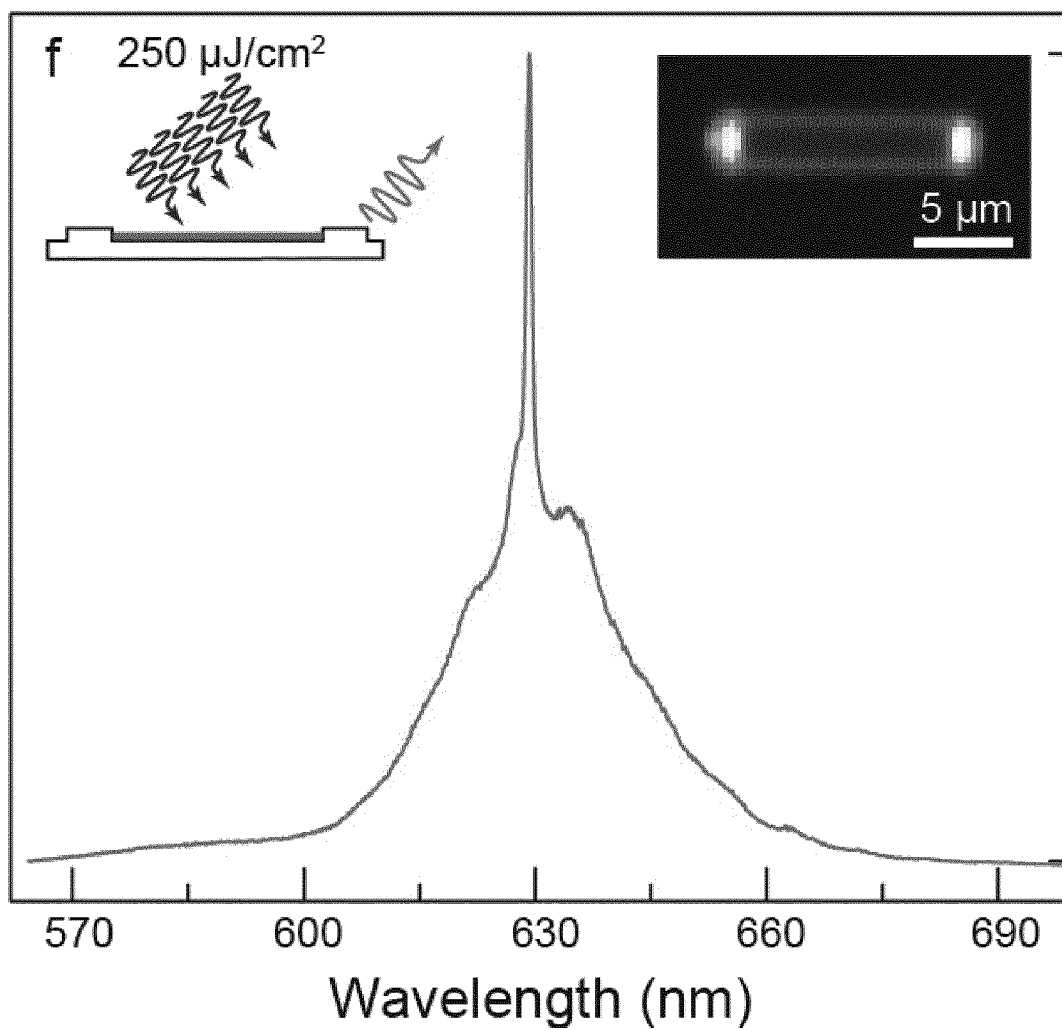


FIG. 9

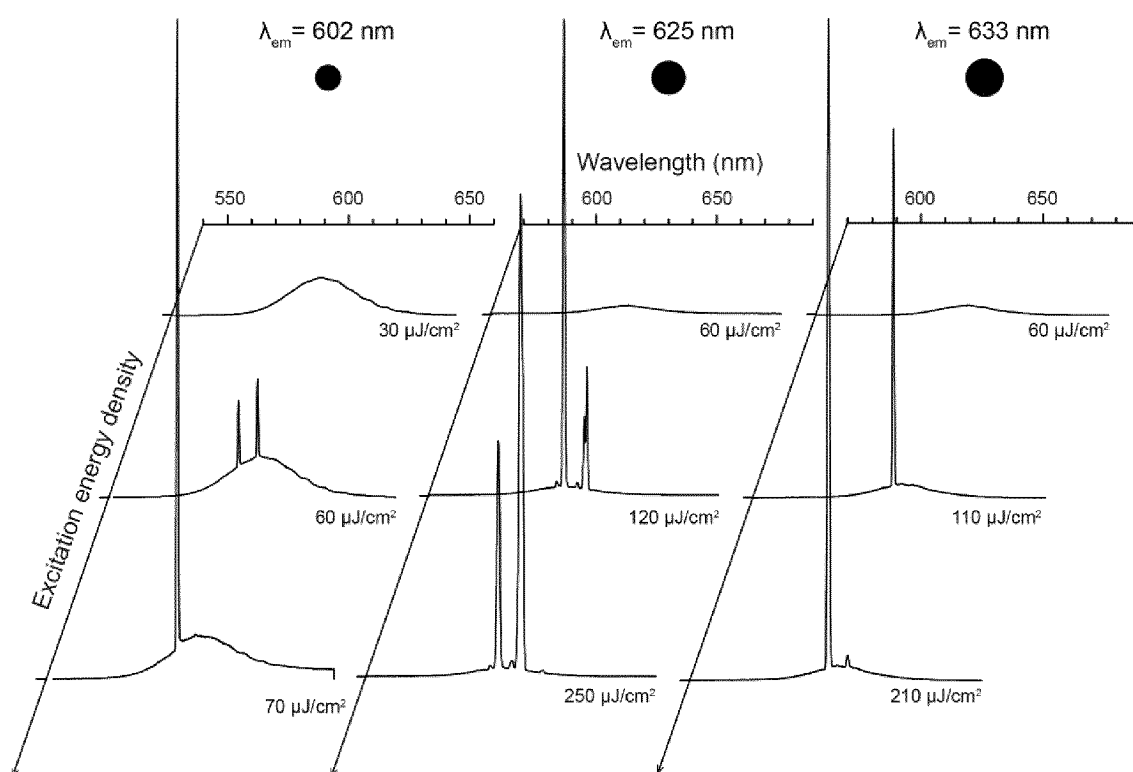


FIG. 10

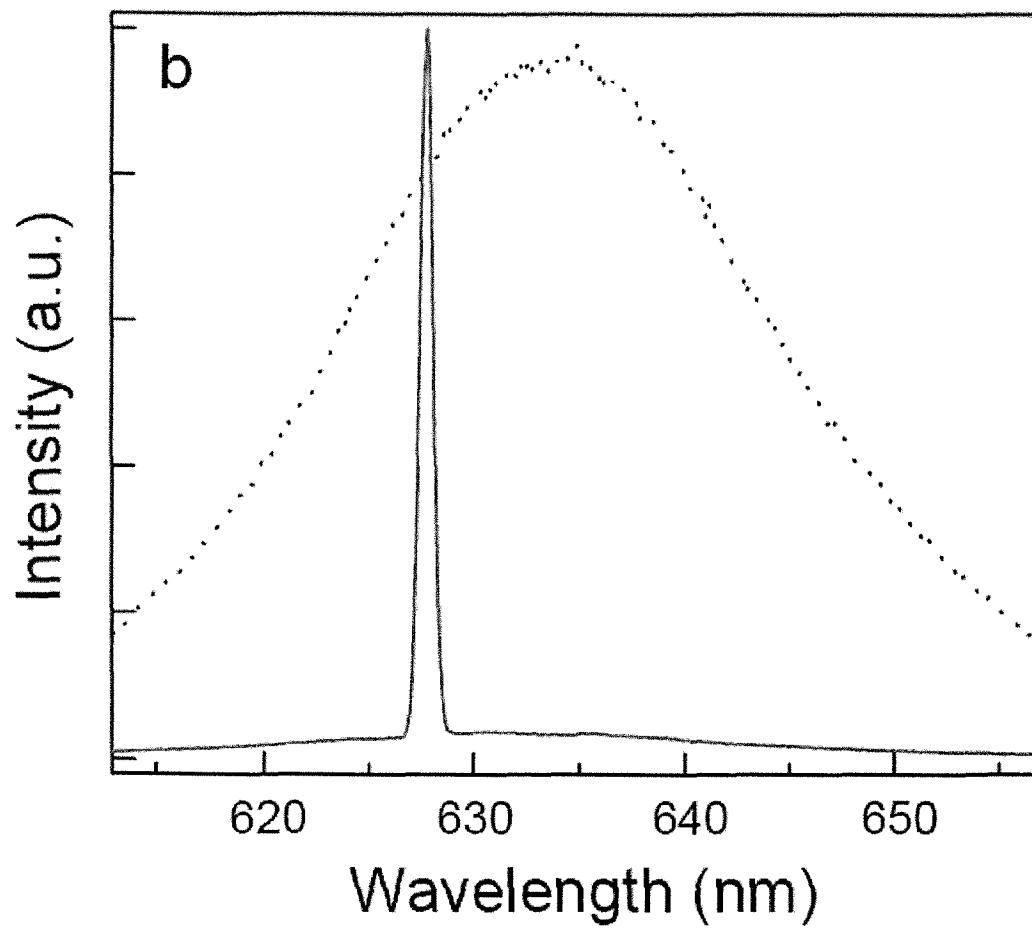


FIG. 11

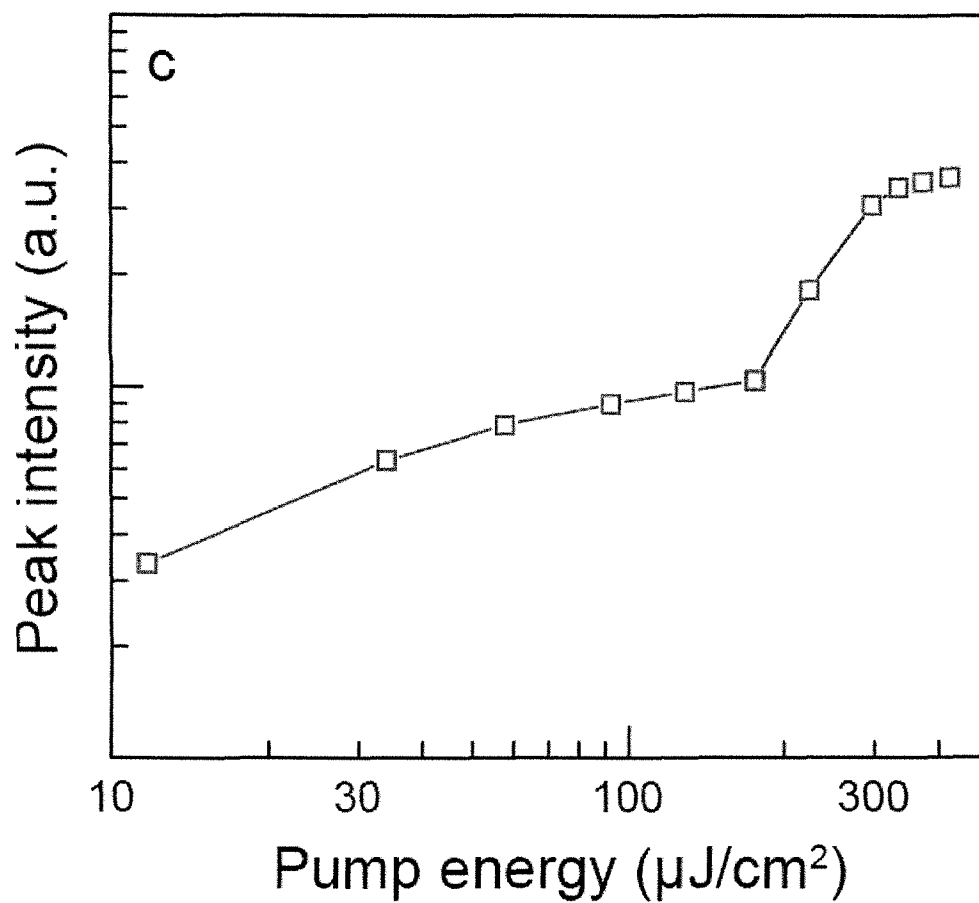


FIG. 12

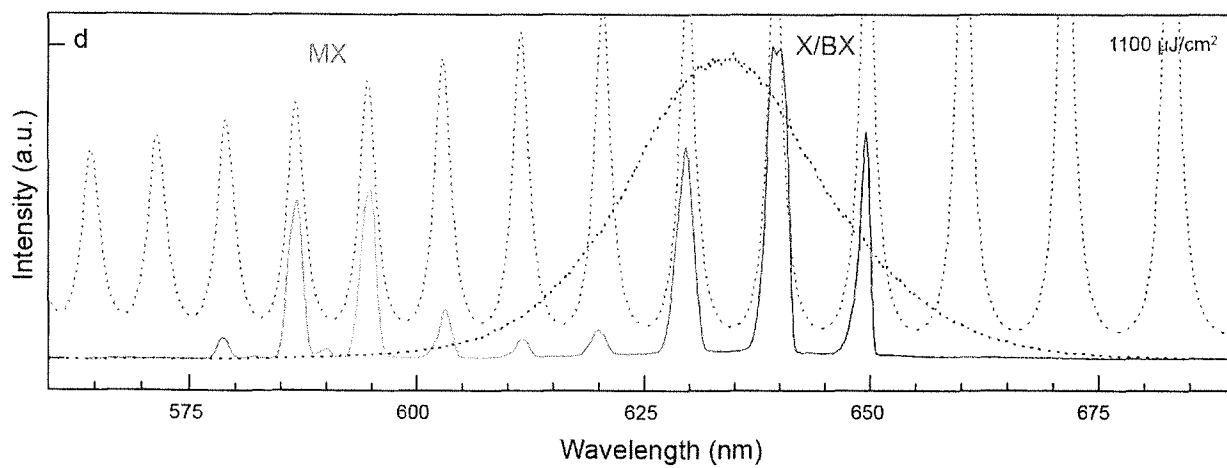


FIG. 13

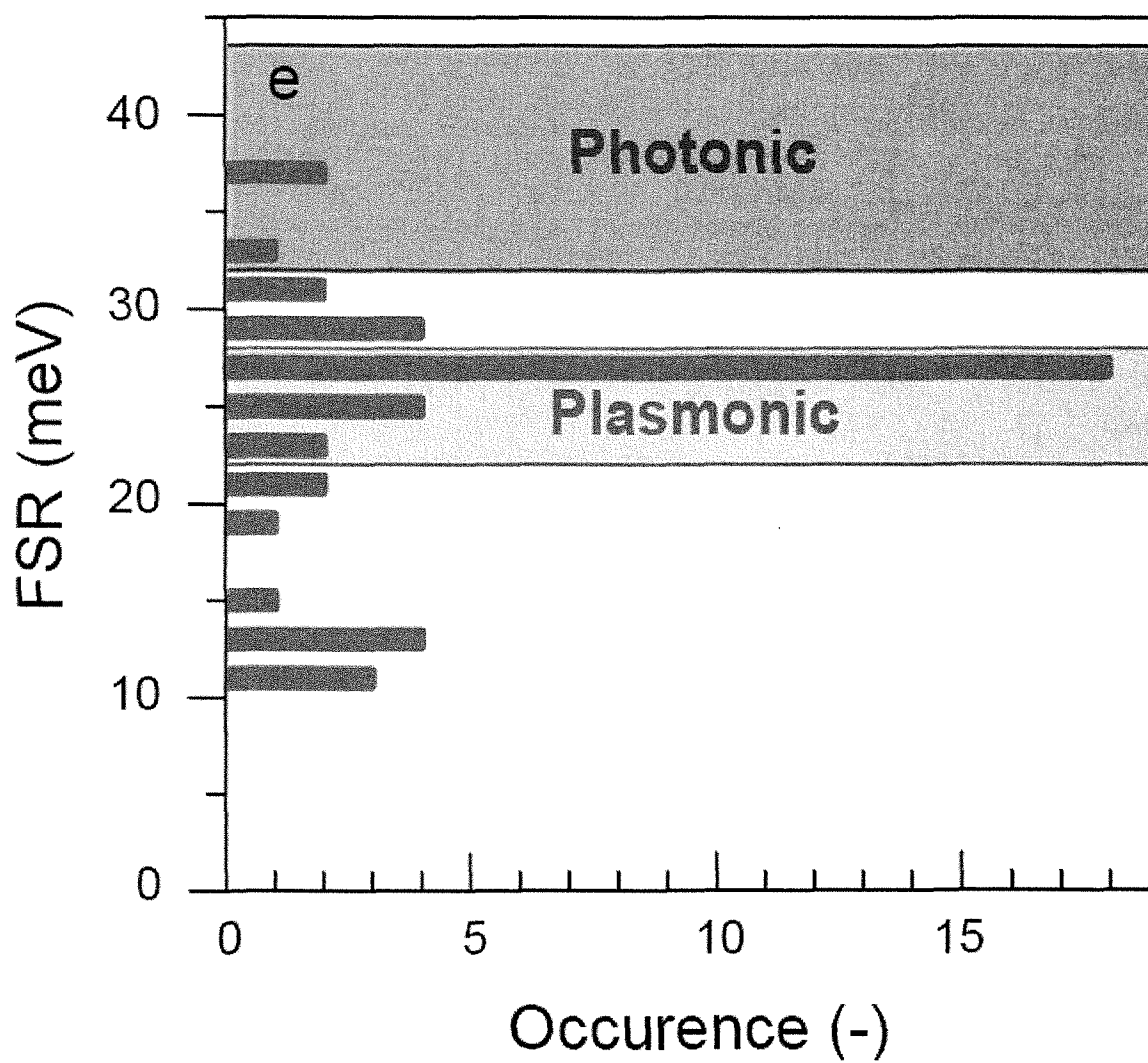


FIG. 14

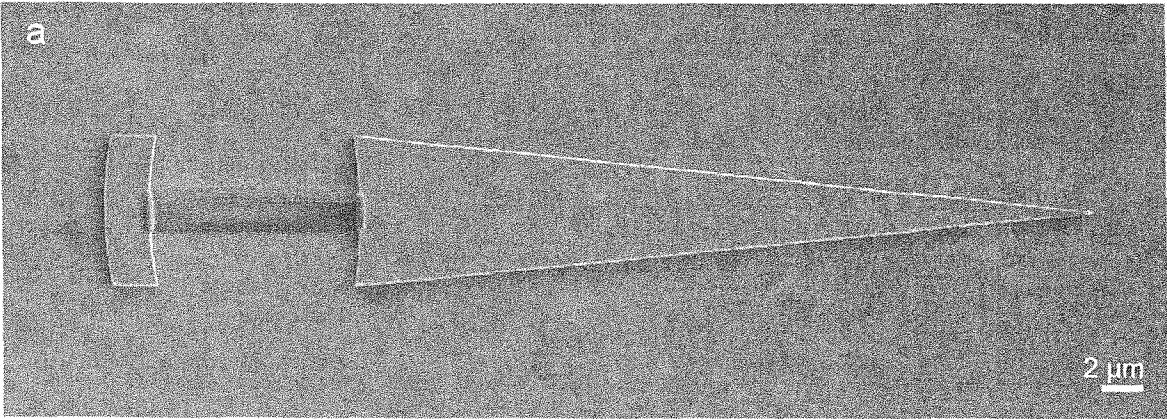


FIG. 15

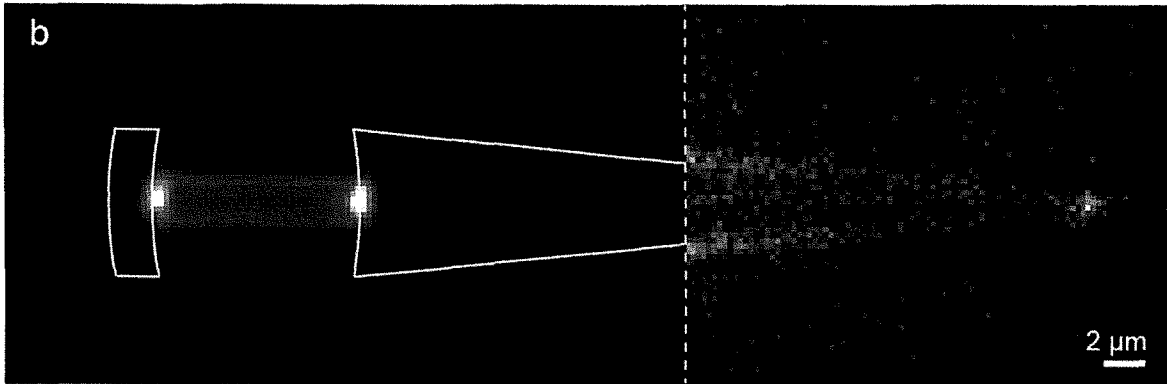


FIG. 16

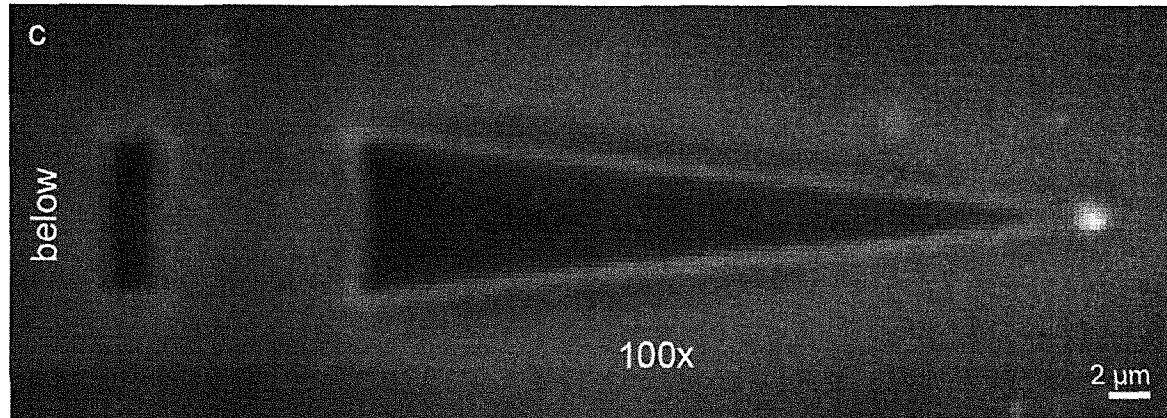


FIG. 17

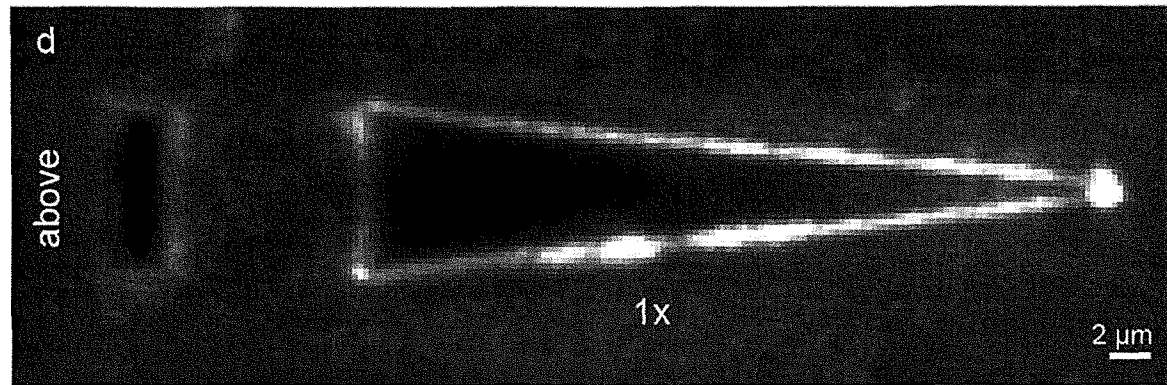


FIG. 18

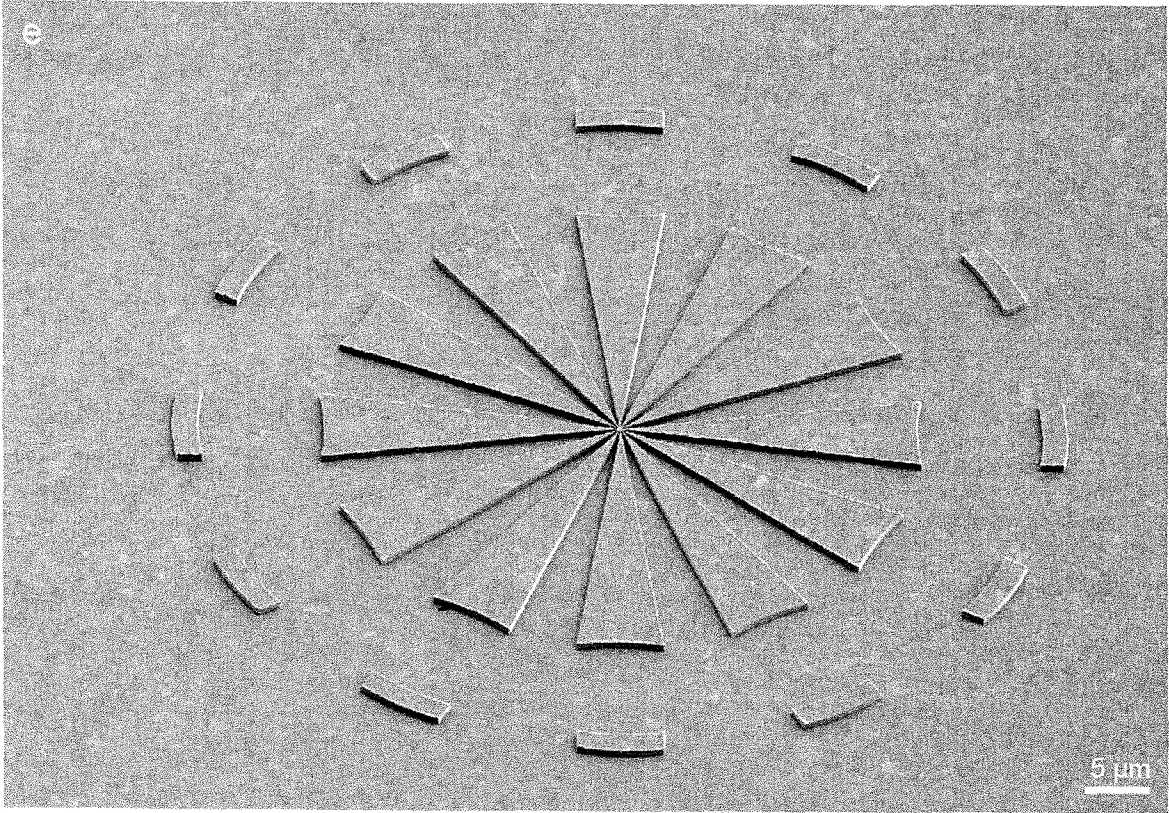


FIG. 19

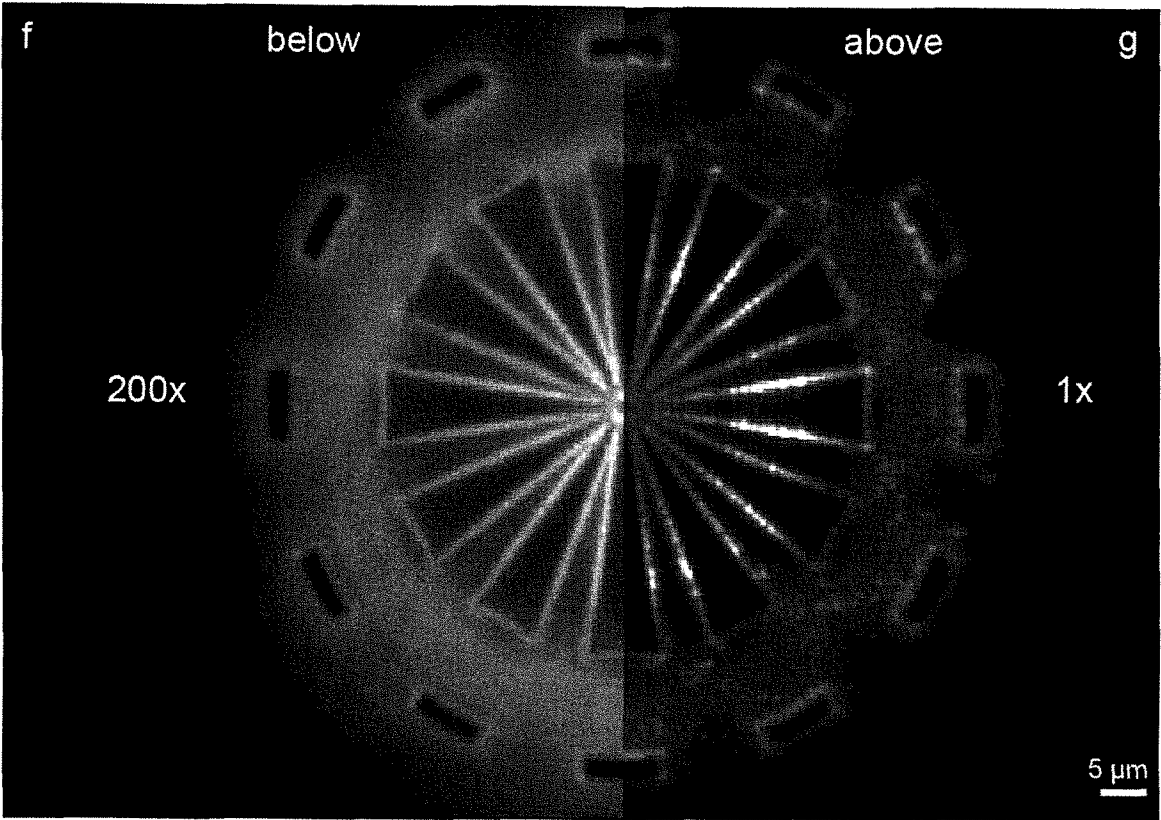


FIG. 20

INTERNATIONAL SEARCH REPORT

International application No
PCT/EP2017/064041

A. CLASSIFICATION OF SUBJECT MATTER

INV. H01S3/06 H01S3/16
ADD. H01S5/10 H01S5/36

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
H01S

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

EPO-Internal, WPI Data

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	ZHU WENQI ET AL: "High-quality-factor cup resonator for plasmonic sensor and plasmon laser", 2016 CONFERENCE ON LASERS AND ELECTRO-OPTICS (CLEO), OSA, 5 June 2016 (2016-06-05), pages 1-2, XP033024725, [retrieved on 2016-12-16] page 1, paragraph 2 - page 2, paragraph 1; figure 1 ----- -/--	1-14, 16-18



Further documents are listed in the continuation of Box C.



See patent family annex.

* Special categories of cited documents :

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Date of the actual completion of the international search

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INTERNATIONAL SEARCH REPORT

International application No

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