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Surface Plasmon Propagation Enhancement via Bowtie Antenna Incorporation in Au-Mica Block Waveguides

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The optimum geometry for waveguide propagation was determined by comparing bowtie and semicircle antenna cuts to a standard plain waveguide with a 635 nm laser. The results of both experimental data and COMSOL simulations proved that the bowtie antenna increased waveguide output in comparison to the plain waveguide with the semicircle pattern showing no enhancement. It was also determined that the propagation was highest when the polarization direction of the laser was perpendicular to the direction of the waveguide for all patterns, while polarization along the propagation direction led to little or no output in all antenna and plain waveguide cases. The waveguide output of the bowtie antenna and plain structures was then measured using a tunable laser for wavelengths from 570 nm to 958 nm under both parallel and perpendicular polarization conditions. The results indicated that the bowtie antenna performed better over the entire range with an average increase factor of 2.12 ±0.40 over the plain waveguide pattern when perpendicularly polarized to the waveguide direction, and 1.10±0.48 when parallel. The measured values indicate that the structure could have applications in broadband devices.

OCIS codes: *(230.7370) Waveguides; (220.4000) Microstructure fabrication; (240.6680) Surface Plasmons; (230.0250) Optoelectronics.*

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1. INTRODUCTION

Surface plasmons (SP) are generated through the interaction of light of a suitable frequency with the electrons on a conductive surface at the metal/dielectric interface[1]. This causes the electrons to oscillate along this surface in resonance with the light wave which, in turn, produces an electromagnetic field which propagates along the surface and decays exponentially into the material. This makes them desirable for use as a means of broadband optoelectronic computation in nanocircuits[2][3]. A range of nanocircuit elements have already been implemented that use SPs to perform the tasks typically carried out by electronic circuits such as information transport and logic computation[4][5]. These elements have also proven capable of operating in a range of wavelength regions including near-infrared allowing for both broadband applications as well as possible silicon chip incorporation[6]. Nanocircuit components which utilize propagating SPs can be fabricated either through the micromanipulation of nanowires and particles, or through direct patterning into a substrate using focused ion beam milling, electron beam microscopy, and/or plasma etching to form more complex patterns out of basic structures such as trenches for more advanced applications[7][8][9]. Various antenna designs such as bowtie, semicircle, and horn have been incorporated into nanocircuit structures to improve the optical or electronic propagation in the structures[10]-[15]. The shape of the bowtie antenna causes strong and confined near-field enhancement with strong scattering resonance behavior in the gap between the two triangles[10][11]. Their unique geometry allows them to behave the same as coupled plasmon resonant pairs while also exhibiting the electromagnetic properties of sharp metal tips[11]. Tests of various bowtie antennas have shown they are able to significantly enhance the optical gain as well as the photoluminescence of certain nanoparticles[12]. In addition; tests into the exact geometry of the bowtie antenna have highlighted the possibility of exciting the antenna at several different wavelengths at the same time and has been shown capable of enhancing silver nanostructures at several different wavelengths depending on the feed gap geometry of the antenna[13][14]. Similarly, the arc shape of the semicircle antenna can allow for broadband incorporation into slit devices and the redirection of the majority of input light into the trench or cavity with a large impedance bandwidth and broad side radiation[15][16].

In this work the enhancement afforded by bowtie and semicircle antennas are evaluated to see if they can improve the waveguided surface plasmon propagation in plain waveguide structures formed in an Au-Mica substrate. In addition the effects of polarization were studied to ensure the waveguided SP output is as high as possible. The bowtie antenna was found

to enhance the waveguided SP by a factor of 2.16 compared to the plain waveguide structure for a 635 nm laser. When the results were expanded to include a range of wavelengths in the region of 570 nm to 958 nm; it was found that, overall, the bowtie antenna performed the best with an average enhancement factor of 2 when the laser was polarized perpendicularly to the direction of the trench due to gap mode propagation enhancement. Conversely; when parallel polarized no notable enhancement was seen due to the waveguide and bowtie both proving equally capable of exciting the surface plasmons indicating that different modes were being excited depending on the laser's polarization. The exact enhancement per wavelength was found to vary depending on the rate of interference experienced by the SP while propagating through the waveguide structure, which would be introduced due to the coupling from the bowtie antenna structure. The information obtained could prove useful for the design and implementation of optoelectronic nanocircuits.

2. ANTENNA TESTING FOR ENHANCED WAVEGUIDE PROPAGATION

In order to test the antenna enhancement experimentally; waveguide structures incorporating either the bowtie antenna, semicircle antenna, or standard trench cut block waveguide design were patterned into an Au-Mica substrate, constructed of 300 nm of Au on several microns of Mica, using a dual-beam FIB to produce gaps 100 nm-200 nm thick. The initial structures were designed to excite the surface plasmons along the surface of the block waveguide. The waveguides were 7-10 μm in length and 1-2 μm in width to test the effects of geometry on the propagation. The bowtie antenna was cut with a separation of 100 nm, and a gap thickness of 80 nm with a triangle side of 2.80 μm ± 0.12 μm for the 2 μm structures and a length of 1.40 μm ± 0.06 μm for the 1 μm structures. The angle used for the bowtie was 10 degrees for the 2 μm structures and 20 degrees for the 1 μm ones. Both angles were found to provide the highest level of enhancement for different bowtie lengths. All antenna parameters were found to perform the best at surface plasmon propagation stimulation based on simulations carried out in COMSOL which are detailed and outlined in the appendix. The structures were illuminated with a 1.5 mW 635 nm laser that was set up with a chopper rotating at 500 Hz to produce a pulsed excitation beam. The laser was focused into a spot using a $\times 50$ objective lens. The output of the waveguide pattern was then aligned with a 1 μm pinhole-lens confocal detection combination so that only the waveguided SP in this region would be detected by an optoelectronic photodiode sensor, which allows the signal to be converted to a voltage reading on an oscilloscope. In order to do this; a signal lock-in amplifier was used that would convert the small output voltage from the sample to a value between 1 and 10 V. The exact conversion depended on the setting used on the amplifier. After the waveguide propagation was measured; a reading of the scattering background signal, when the detector is positioned away from the waveguide output, was taken and subtracted from the result to remove error from the measured waveguide output.

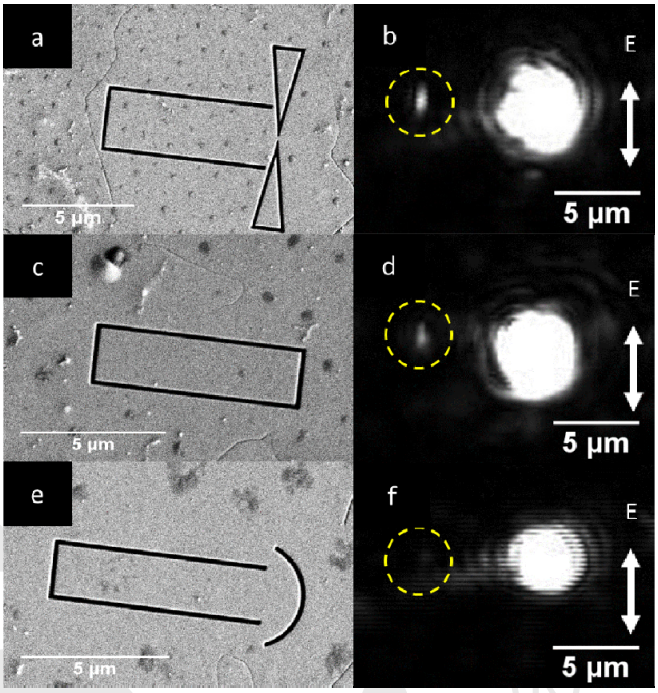


Fig.1: An SEM image and the waveguided SP produced from a 635 nm chopped CW laser for (a,b) the bowtie antenna, (c,d) plain trench cut block waveguide, and (e,f) semicircle antenna cuts. Waveguide propagation is strongest for the bowtie antenna due to increased coupling. SEM images were taken after waveguide output experimentation had concluded. (Output is highlighted by the yellow broken circle).

The results indicated that, for all lengths and widths, the bowtie antenna performed the best by a factor of 2.16 over the plain trench cut waveguide. The semicircle antenna produced the lowest waveguide output of all on average only 0.88 of the output measured by the plain trench cut waveguide structure. As shown in Fig.1; the waveguide output is strongest from the bowtie antenna pattern when compared to those of the trench and semicircle. The semicircle antenna seems to perform poorest as, despite the coupling afforded by the antenna the separation between the trench and the antenna, and the wider collection area, it results in less of the waveguided SPs being directed into the trench and produces a weak output. The bowtie antenna, conversely, performed much better due both to the localized region of the field and the coherent interference produced between the input laser and the diffracted waveguided SPs from the bowtie regions resulting in a much stronger waveguided SP output in comparison to that obtainable from the plain trench cut waveguide structure.

3. POLARISATION EFFECTS ON WAVEGUIDE PROPAGATION

The effect of polarization on the waveguide output was also determined by introducing a ½ wave plate and polarizer pair to change the polarization of the beam. As the laser itself was of known polarization of 90 degrees; by altering the waveplate and polarizer pairs; the polarization of the beam could be rotated by ten degrees and a measure of the output was made as before for the new polarization value. For these tests the 7 μm $\times$ 2 μm pattern structure was used for all cases to allow for an accurate comparison.

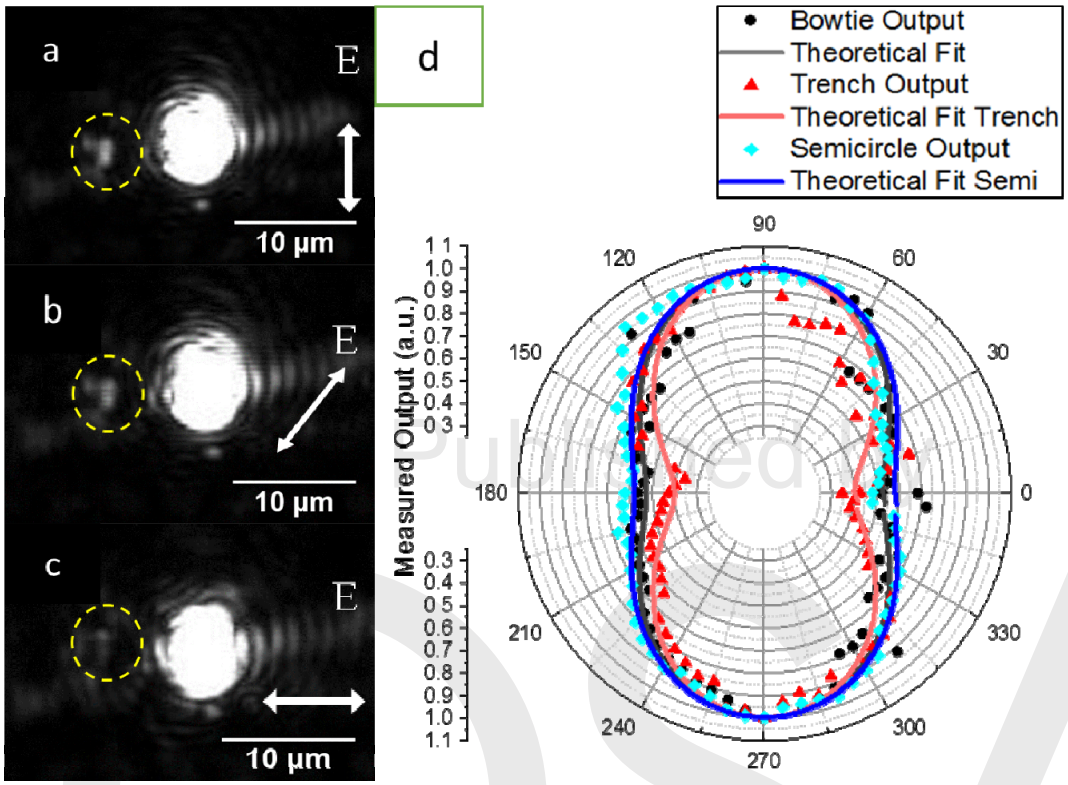


Fig. 2. The change in waveguided SP output for the 7 µm × 2 µm bowtie antenna for input lasers polarized at (a) 90, (b) 50, and (c) 0 degrees. The waveguide output is strongest when the propagation is perpendicular to the orientation of the waveguide direction at approximately 90 degrees. (Waveguide output is highlighted by the yellow broken circle.) The plots show the measured waveguide output and the theoretical fit for all three patterns (discussed below) in (d).

Fig.2 shows the effect of polarization angle change on the waveguided output for the bowtie antenna. It was found that, for all patterns, the waveguide output was strongest when it was polarized perpendicular to the propagation direction of the block waveguide. Conversely, there was little to no waveguide output when the laser was polarized parallel to the block waveguide direction. At different angles of polarization, the output is reduced. The output of the waveguided SPs is regulated by the amount of loss experienced by the contributions of both the main surface plasmon excitation TM (0 degree) and higher order TM (90 degree) modes. The polarization vector is made of a horizontal and vertical component from these two modes. When the beam interacts with the waveguide; the modes decouple based on the input coupling coefficient. As a result, the propagating SPs follow the equation[17][18]:

$$I(Total) = I_{90}\cos^2(\theta - 90) + I_0\cos^2(\theta - 0) \quad (1)$$

Where I is the irradiance, and θ represents the angle of the laser's polarization. Each of the polarization plots were normalized to 1 which represents the 90 degree polarization situation. The value for I_0 differed depending on the pattern; which would make sense as the different patterns couple light in differently resulting in an alteration to the coupling efficiency depending on the cut. The ratios of the mode output, when each are dominant for the bowtie, semicircle, and plain waveguide patterns were found to be 1:0.52, 1:0.58, and 1:0.40 respectively which represent the coupling mode coefficients. This is obtained by getting the ratio between the maximum and minimum values for each curve in figure 2. The lower the ratio; the better the pattern is at propagating both the standard TM and higher order modes. As seen when studying these values; the plain waveguide structure has a significantly higher ratio value in comparison to both the bowtie and the semicircle patterns. While the semicircle antenna had a slightly lower ratio compared to the bowtie; its lower power output and weaker waveguided SPs decrease the effectiveness of its use without additional external coupling enhancement. Both antenna patterns resulted in better mode ratios indicating that they are both better at coupling in the higher order mode than the standard waveguide pattern. The theoretical fits were calculated based on the equations and compared to the data. All followed the obtained data well as shown in Fig.2.

4. BOWTIE ANTENNA ENHANCEMENT IN BROADBAND APPLICATIONS

In order to test the bowtie antenna's performance for broadband applications in comparison to the plain waveguide; the 7 µm × 2 µm patterns were tested using a tunable wavelength laser. A variety of wavelengths were chosen in the region of 570 nm-958 nm and a wave plate was introduced to ensure that the waveguide was propagating when both parallel and perpendicular to the waveguide direction. The laser was again chopped by the inclusion of a chopper rotating at 500 Hz.

A NA 0.9 x 100 objective was used in this setup. The measurements were taken repeatedly over the course of several days, to reduce any error in the measurements. In addition; a separate set of COMSOL simulations were carried out for the same wavelength and polarization conditions for comparison. For both simulations and experimental data; the beam waist of the laser was approximately equal to the wavelength of the light meaning that for each wavelength each pattern received the same amount of light to potentially couple in. The measured waveguided output was normalized in each case by taking a measurement of the laser light incident on the substrate, for each wavelength, before testing the patterns. This value was then compared to the waveguide propagation output of the structures to get a correct measurement of the device performance.

Fig.3 shows the obtained SP waveguided output from both the experimental and simulated data when the laser was perpendicularly polarized. The same is shown in Fig.4 for the parallel condition. As shown, it was found that the bowtie antenna structure performed as well, or better, then the plain waveguide pattern in both cases. Conversely, simulations for the semicircle antenna yielded very low output for both polarization cases. Due to this fact; the experimental testing focused on the bowtie enhancement. For both the simulation and experimental data the bowtie showed an average enhancement across the wavelengths of 2.05 ± 0.82 and 2.12 ± 0.40 respectively when perpendicularly polarized. This was significantly reduced both for the simulations and experimentally to 1.05 ± 0.23 and 1.10 ± 0.48 for the parallel configuration respectively. While there is some enhancement apparent in the 600-700 nm region for the parallel polarized experimental data; it should be noted that the error was generally higher than that for the other wavelengths, and the enhancement still remained, on average, below a factor of two. Due to the data otherwise matching the simulations well; the bowtie's performance is still considered to have no clear advantage over the plain waveguide in this configuration. For both polarizations; the exact enhancement value was found to depend on interference experienced by the plasmon or optical modes when propagating through the trench due to the coupling which occurs in the bowtie antenna. The reason for the difference in enhancement for the different configurations is thought to be due to the enhancement of different modes. In the parallel polarization configuration; the bowtie antenna and the perpendicular trench cut are both almost equally capable of exciting the surface plasmon modes. As such, both produce similar waveguided outputs. The perpendicular polarization condition instead excites the gap mode from the structure resulting in the enhanced performance of the bowtie[18]-[22].

This result is supported by COMSOL simulations and experimental data obtained of line cuts instead of waveguides which are 7 μm × 100 nm wide where the parallel configuration shows increased enhancement from the bowtie up to several orders of magnitude over the line cut. In addition, simulations of the bowtie structure on its own along with a single perpendicular 2 um line cut showed that both were capable of enhancing the surface plasmons without the directional preference of the block waveguide or line cut (shown in appendix.)

The beam waist of the laser was close to that of the wavelength meaning that there was some variation during the testing. Through simulations; it was found that increasing the beam waist resulted in a similar increase in the propagation output of the bowtie antenna; i.e. an increase x 2 of the beam waist resulted in an enhancement of 35 % in the propagation output; due to a larger area of the bowtie antenna being illuminated. When the beam waist was reduced there was a similar decrease in the propagation output with a beam waist reduced by half producing a reduction of 35 % in the output signal. Simulations indicated that there was no noticeable change in the output of the block waveguide. This indicates that there is still some enhancement offered by the bowtie antenna for smaller beam widths.

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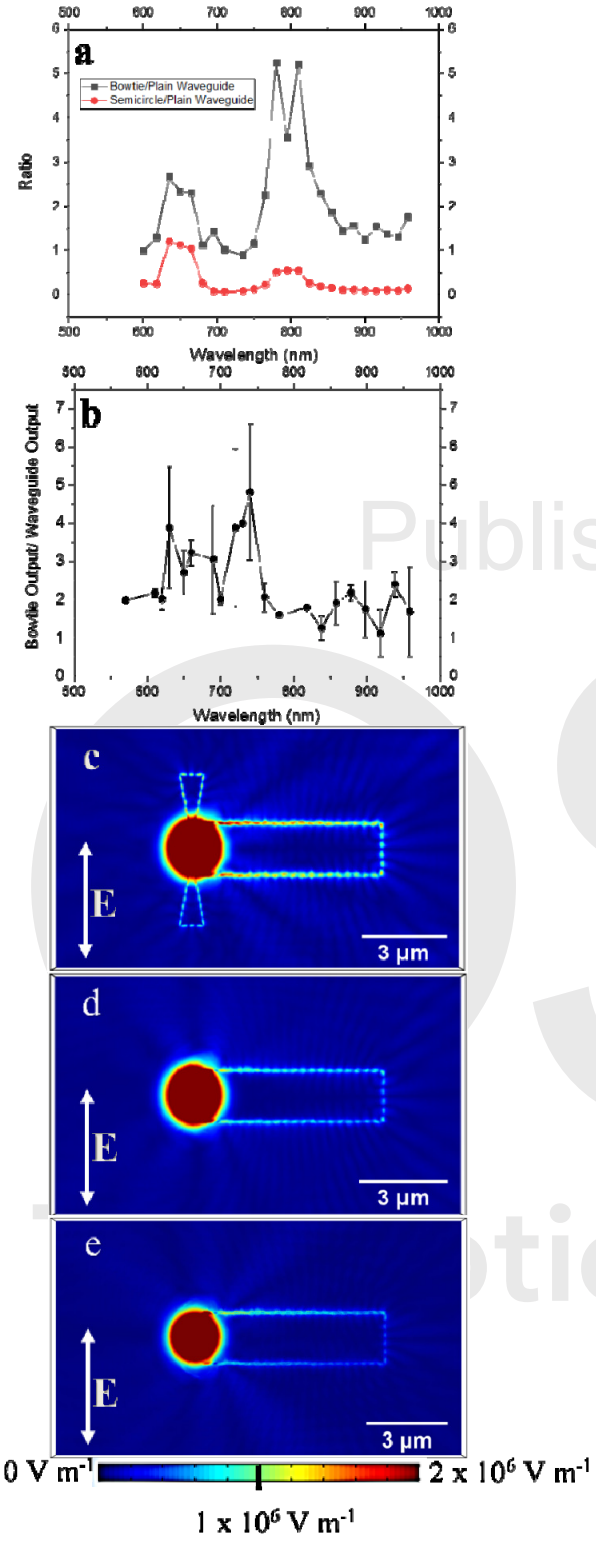


Fig. 3. The data collected (a) via simulations showing the ratio of (black square) bowtie waveguide and (red circle) semicircle waveguide output over a plain block waveguide output and (b) the experimental data for the ratio of bowtie output to block waveguide output for the wavelength region 570-958 nm for a perpendicularly polarized beam. The simulated electric field propagation is shown for (c) the bowtie, (d) the waveguide, and (e) the semicircle antenna at 720 nm.

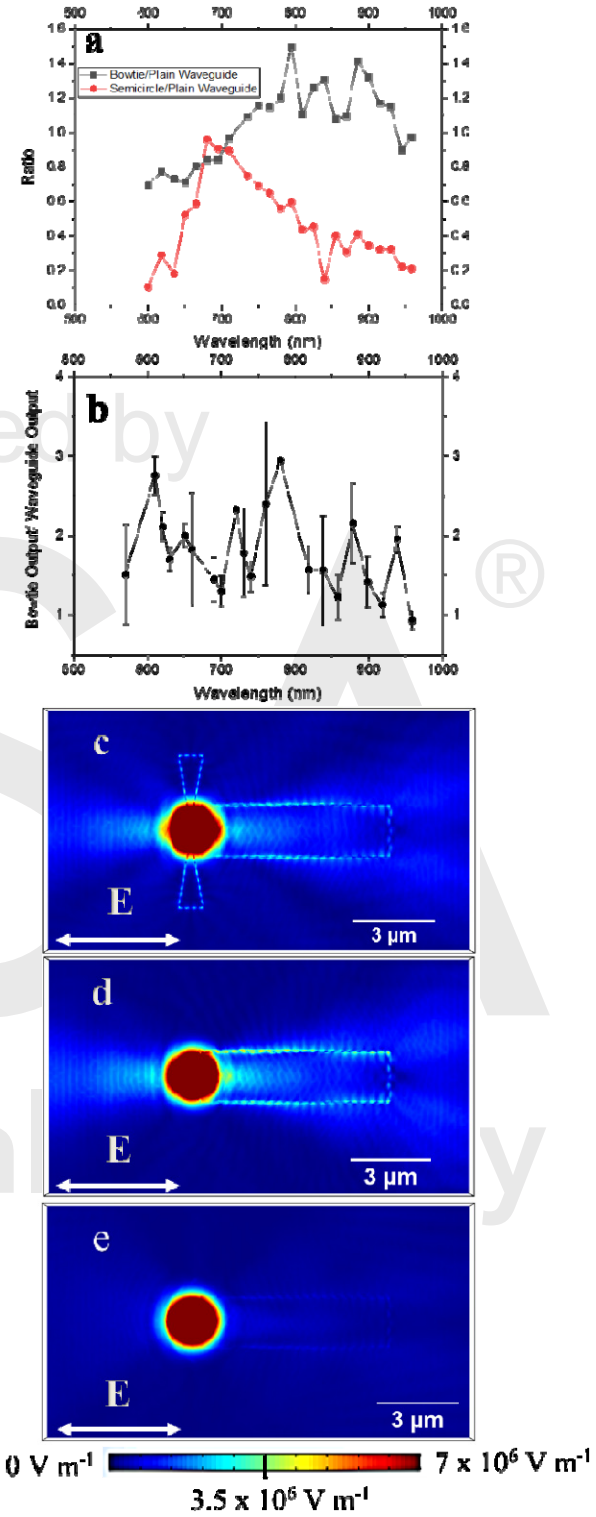


Fig. 4. The data collected (a) via simulations showing the ratio of (black square) bowtie waveguide and (red circle) semicircle waveguide output over a plain block waveguide output and (b) the experimental data for the ratio of bowtie output over block waveguide

output for the wavelength region 570-958 nm for a parallel polarized beam. The simulated electric field propagation is shown for (c) the bowtie, (d) the waveguide and (e) the semicircle antenna at 720 nm.

The efficiency of the bowtie antenna at coupling in light was determined to be on average 4.75 ± 1. 31 %. While this value is low compared to other more complex antenna schemes[23][24][25]; the straightforward method for the antenna's fabrication could make it a cheap alternative when only slight enhancement is required for an optoelectronic device.

5. CONCLUSIONS

In conclusion, the effects of bowtie and semicircle antenna on waveguided SP enhancement were investigated through their comparison with a plain waveguide structure. It was found that, for a 635 nm laser, the bowtie antenna provided enhancement by a factor of 2.16 over the plain structure due to the waveguide coupling afforded by its design. In contrast, the semicircle antenna proved the least effective; proving capable of only 0.88 the waveguide output of the plain structure. When the polarization of the laser was altered; it was found that, in all cases, the waveguided SP output was greatest when the waveguide was polarized perpendicular to the direction of propagation of the trench. In addition; the exact variance in polarization from maximum to minimum was seen to change depending on the pattern used, which would make sense as each one couples light differently. When the bowtie and trench patterns were tested for both parallel and perpendicular polarizations, with wavelengths in the region of 570 nm-958 nm, the bowtie antenna was found to perform the best with an average enhancement of 2.05 ± 0.82 and 2.12 ± 0.40 from the simulation and experimental data respectively when the polarization is perpendicular to the trench direction, and 1.05 ± 0.23 and 1.10 ± 0.48 respectively when the beam was parallel. The change in enhancement is believed to be due to the excitation of different modes; with the structures both exciting the surface plasmons to similar levels when the input light is parallel polarized to the direction of the trench. When the input light is perpendicularly polarized the gap mode through the structure is instead excited resulting in the bowtie antenna producing an enhancement of 2.16 over the plain trench structure due to gap mode enhancement. The results provided could prove useful for broadband or nanocircuit design applications or optimal waveguide coupling[26][27][28]. More complex patterns could be cut into the Au-Mica substrate to further test the enhancement of the bowtie antenna in these conditions[29]-[31]. Further work could also be carried out into the effects of other antenna designs such as the horn and slot antennas that should also provide enhancement in nanocircuit devices[32]-[34].

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Appendix 1: The Design of COMSOL Simulations

COMSOL simulations were carried out to determine the optimum waveguide cut pattern for the waveguide propagation in an Au-Mica sample. A 3d model was used to properly model the polarization effect of the reflected/ backscattered fields. A 3d Gaussian beam was applied to simulate the excitation beam and the frequency domain stationary solutions were obtained for a series of simulation parameter sets. The thickness of the Au was set to 300 nm while the Mica was several microns thick. For the simulations, a standard 7 μm long trench was used with a width of 2 μm was used to form the regular waveguide structure. The wall thickness of the trenches was set to 100 nm and the patterns were set to cut 200 nm into the Au. Two main configurations were used aside from the standard waveguide structure; a semicircle and bowtie antenna structure. The simulation was set to illuminate the entry point of the waveguide structure using a 635 nm laser beam, with the main point of interest being the strength of the electric field upon exiting the trench at the opposite end. The semicircle pattern had variations in the distance, thickness, and angle to determine the optimum output signal. For the bowtie, the thickness of the walls, and the distance between the two triangle antennas were varied for optimum signal output. A schematic of the simulation and the data collection method is shown in Fig A1.

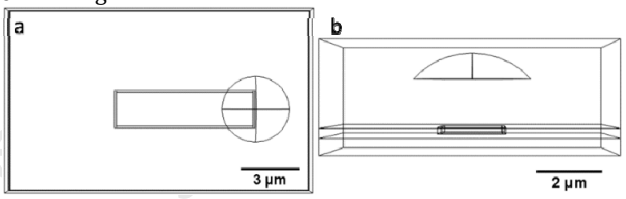


Fig A1: The geometry used for the simulations of the bowtie and antenna structures. The Gaussian beam excites the sample at the left end of the structure. The circular structure in (a) and (b) represents the lens in an optical setup: It is designed so that it collects the intensity output from the sample over the same area as the NA of the lens in the lab. A line cut straight through the 7 μm length of the trench was used to measure changes in the electric field as the waveguide propagates through the central section cut out by the trench.

The optimum parameters were found by measuring the electric field output of the patterns. The regular waveguide pattern was run as a control standard.

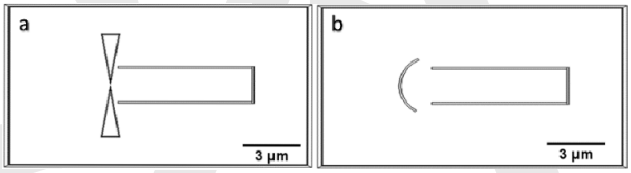


Fig A2: The optimum geometry determined for (a) the bowtie and (b) the semicircle antenna.

The finalized geometries were compared in terms of output intensity by integrating the electric field over a partial sphere. The collection area of the sphere was set to match the NA of the microscope lens used in the lab. For these the wavelength of the Gaussian beams of 635 nm had a polarization parallel to the direction of the trench. When tested; the bowtie gave an enhancement of 2.30 over the plain waveguide structure; while the semicircle gave enhancement of 1.35. Both patterns were thus considered suitable for further testing.

The structure of the optimized designs are shown in fig. A2. Optimum geometry for the bowtie antenna was found to include a cut with a separation of 100 nm, and wall thickness of 80 nm- 100 nm with a triangle length of 2.80 μm ± 0.12 μm. The angle used for the bowtie was 10 degrees. For the semicircle cuts; a partial circle structure was used with a radius of 1.45 μm and an arc length of 2.9 μm.

Appendix 2: Beam Coupling Through Entrance Structures Only

To highlight that the trench patterns, propagating light which was parallel polarized to the trench direction, were exciting the surface plasmons themselves; the simulations were rerun with only the bowtie and perpendicular trench wall present. As shown in fig. A3; both excite the surface plasmons and send them propagating in both directions parallel to the input polarization without the need for the additional directionality afforded by the trench structure. The output in both cases is shown to be comparable to that measured when the trench is present which further highlights the fact that the structures in this case are exciting surface plasmons.

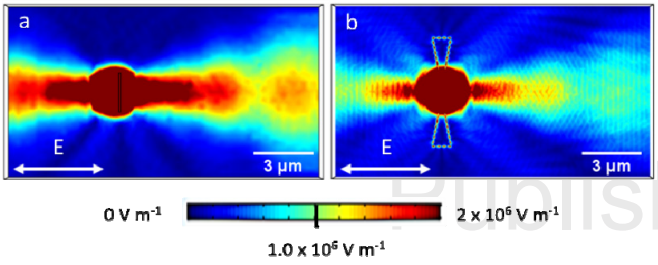


Fig A3: The electric field propagation for (a) the plain single block waveguide and (b) the bowtie antenna when illuminated with a parallel polarized Gaussian beam at 750 nm. As shown; both the antenna and the trench cut are able to sufficiently excite the surface plasmons in two directions parallel to the theoretical direction of the trench even when the full structure is not present. Here the trench cut is shown 10 nm below the surface to allow the trench wall used for the excitation to be seen.

Appendix 3: Calculating the efficiency of the bowtie antenna

In order to determine the bowtie efficiency through simulations; a second bowtie antenna was placed at the end of the end of the block waveguide as shown in fig. A4. For these tests the end wall of the waveguide was removed to prevent the end coupling affecting the efficiency calculation. A second spherical structure was placed over the output antenna so that the intensity output from its entire surface could be collected. This was then compared to the power of the beam incident on the bowtie antenna. The integration lens for the waveguide output was kept in place so that the light coupled out of the waveguide could be subtracted from the value obtained to improve the accuracy of the efficiency measurement.

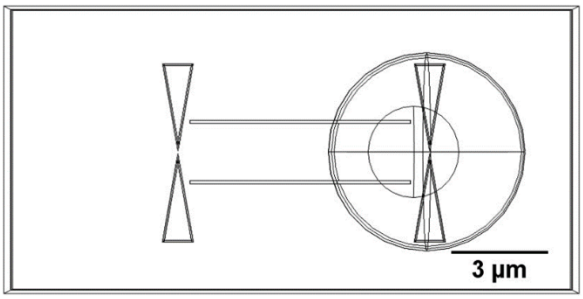


Fig A4: The geometry used to determine the efficiency of the bowtie antenna.

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