Abstract—This paper reviews recent work on device applications of optical antennas. Localized surface plasmon resonances of gold nanorod antennas resting on a silica glass substrate were modeled by finite difference time-domain simulations. A single gold nanorod of length 150 or 550 nm resonantly generates enhanced near fields when illuminated with light of 830 nm wavelength. A pair of these nanorods gives higher field enhancements due to capacitive coupling between them. Bowtie antennas that consist of a pair of triangular gold particles offer the best near-field confinement and enhancement. Plasmonic laser antennas based on the coupled nanorod antenna design were fabricated by focused ion beam lithography on the facet of a semiconductor laser diode operating at a wavelength of 830 nm. An optical spot size of few tens of nanometers was measured by apertureless near-field optical microscopy. We have extended our work on plasmonic antenna into mid-infrared (mid-IR) wavelengths by implementing resonant nanorod and bowtie antennas on the facets of various quantum cascade lasers. Experiments show that this mid-IR device can provide an optical intensity confinement 70 times higher than that would be achieved with diffraction limited optics. Near-field intensities \( \sim 1 \text{ GW/cm}^2 \) were estimated for both near-infrared and mid-IR plasmonic antennas. A fiber device that takes advantage of plasmonic resonances of gold nanorod arrays providing a high density of optical “hot spots” is proposed. Results of a systematic theoretical and experimental study of the reflection spectra of these arrays fabricated on a silica glass substrate are also presented. The family of these proof-of-concept plasmonic devices that we present here can be potentially useful in many applications including near-field optical microscopes, high-density optical data storage, surface enhanced Raman spectroscopy, heat-assisted magnetic recording, and spatially resolved absorption spectroscopy.

Index Terms—Gold nanoparticles, near-field optics, surface-enhanced Raman spectroscopy (SERS), surface plasmons (SPs).

I. INTRODUCTION

Optical applications of metals have been limited to reflectors, due to their large free electron densities [1], even in the optics laboratories until the middle of the last century. Surface plasmons (SPs) and surface plasmon polaritons (SPPs) have provided a basis for new applications [2]–[7]. Nowadays, they are of interest in a broad range of research fields including near-field optical microscopy [8]–[12], chemical and biological sensing [13]–[16], single molecule spectroscopy [17]–[20], subwavelength optics [20]–[33], left-handed metamaterials [35]–[46], and high-density optical data storage [47]–[54] among many others.

The SPP modes are physical solutions of Maxwell’s equations at an interface between a metal and a dielectric. These interface waves are possible since a metal has a negative dielectric constant whereas that of the dielectric is positive [55]. This yields a mode that decays evanescently into both materials and propagates, accompanied by a significant longitudinal electric field component along the interface, with a propagation length associated with losses in the metal.

For frequencies below the terahertz range, in which metals behave like a perfect conductor, the SPs exhibit a linear dispersion since most of the energy is in the tail of the SPs that decays into the dielectric side of the interface. However, at optical frequencies, the SPs have unique dispersion characteristics; they can have extremely large propagation vectors (i.e., ultraviolet wavelengths at visible frequencies) since metals have strongly frequency-dependent dielectric constants [55]. This property makes SPs important for nanophotonics since it allows light to be concentrated to subwavelength regions [3], [4].

Exciting SPPs on metal surfaces requires care at optical wavelengths [13]. First, the surface-parallel wavevector mismatch needs to be compensated for. The most commonly used schemes for exciting SP modes are prism and grating coupling configurations [7]. The latter can compensate for the momentum mismatch by taking advantage of the periodicity of the grating. The former usually involves a glass prism. When light is incident on the prism–metal interface at the correct angle, the SPs on the top metal–air interface will be excited since the wave vector in the glass prism can be as large as that of the SP mode. Sensors based on prism coupling can provide single atomic layer sensitivity [14], [15] since SP resonances are very sensitive to changes in the vicinity of surface due to their evanescent tails. This technology is commercially available for applications in life sciences from Biacore AB [56].

Ebbesen’s pioneering work [32] on subwavelength hole arrays in silver films demonstrated that the power transmitted through such a hole array is higher than that is impinging directly on the total area of the holes. This “extraordinary” transmission...
can be explained by coupling of SPs on either side of the metal film and scattering by the hole array [34].

Metallic nanoparticles offer near-field enhancement due to their localized SP resonances [57]. Gold and silver colloidal nanoparticles are responsible for the red and yellow colors in medieval stained glass windows [57]. Although Faraday studied metallic nanoparticles, the first rigorous theoretical treatment was introduced by Gustav Mie in 1908 [58]. Mie presented an exact solution to Maxwell’s equations that accounts for the extinction spectra of metallic nanospheres of arbitrary size [59].

When a metallic nanosphere is illuminated with a plane wave, a conduction current oscillating at the same frequency as the incident light will be induced in the nanoparticle. If we take a snapshot of the charge distribution in the particle, we would see electrons piling up on one side and positively charged ions on the other. In the near field of the particle, the electric field is larger than the incident field due to the Coulomb field generated by these charges and dominated by the nonpropagating components that decay rapidly with distance. This singular behavior of point dipoles accounts for the very short range of the optical near fields [57].

In recent years, a variety of schemes taking advantage of localized near fields generated by metallic nanoparticles have been proposed to use them as optical nanoantennas [60]–[69]. Optical antennas consisting of nanometer size metallic particles can be used to improve the size mismatch between the diffraction limited spot of the excitation light and fluorescent molecules that are much smaller than the excitation wavelength [65]. Optical antennas can produce very high near-field intensities when they are optically excited with a wavelength suitably matched to the antenna size due to their localized SP resonances [66]. Passive optical antennas were first demonstrated in the microwave regime by Grober and coworkers [70]. Also, mid-infrared (mid-IR) passive antennas [60] and bowtie antenna-based bolometers [71], [72] have been implemented.

Of particular interest are resonant strongly coupled nanorod optical antennas that lead to a large intensity enhancement in the gap. Aizpurua et al. [73] carried out a comprehensive theoretical analysis of field enhancement with single and coupled metallic nanorods. More recently, resonances of nanorod optical antennas designed for near-infrared wavelengths were characterized using two-photon photoluminescence generated in gold [66]. A scanning probe microscope with a bowtie antenna probe for visible spectrum was also utilized for imaging single semiconductor quantum dots [67], [68].

Near-field enhancement generated by optical antennas is useful for surface-enhanced Raman spectroscopy (SERS) [17]–[19], [64]. Recently, metallic nanoparticles have been utilized in biosensing [74], cancer treatment [75], and near-field probes [10]. Optical nanoantennas can also increase the excitation and emission rates of fluorescent molecules [11], [12].

This paper is organized as follows. In Section II, we discuss our simulation results on single and double gold optical antennas. Section III discusses our experimental results with near-infrared and mid-IR active plasmonic laser antennas. In Section IV, a fiber device based on plasmonic resonances of gold nanorod antenna arrays is proposed, and measurements of SP resonances in these arrays fabricated on glass substrate are also presented.

II. OPTICAL ANTENNA DESIGN AND MODELING

A. Single and Coupled Nanorods

We first investigated plasmonic resonances of single gold nanorods on a silica glass substrate as shown in Fig. 1. A commercial finite difference time-domain (FDTD) code was used for the simulations. For the modeling, perfectly matched absorbing boundary conditions were introduced in all directions in order to eliminate spurious reflections. The single plasmonic nanorod antenna is illuminated from the substrate side by a monochromatic plane wave excitation of 830 nm free-space wavelength polarized along the nanorod length.

When the plane wave is incident on the gold nanorod, the conduction electrons in the metal respond to the electric field by generating a polarization field that leads to charge accumulation at the opposite ends of the nanorod. This charge buildup, which is quasistatic in the dipole approximation, results in a strong optical near-field enhancement at the antenna ends [73]. We have calculated the peak intensity enhancement at the same level as the top nanorod surface. By varying the length L of a single nanorod, we determined the resonant antenna lengths for which the near-field enhancement is maximum. The ends of the nanorods are realistically rounded off with a 20 nm radius of curvature. The nanorod has a square cross section of 40 nm × 40 nm. A Drude model, fitted to the experimental literature values [76], is used for the dielectric constant of gold. The refractive index of the substrate is n = 1.46.

Fig. 1. Simulated geometry: single gold nanorod resting on a SiO2 (n = 1.46) substrate.
near fields. Fig. 2 shows the time-averaged intensity enhancement at the nanorod end normalized to the incident intensity as a function of the antenna length. The first resonance occurs for a nanorod length of 150 nm and the second for 550 nm. These resonances are analogous to the $\lambda/2$ and the $3\lambda/2$ resonances, respectively, of an RF antenna. For $L = 150$ nm, the near-field intensity is $\sim 400$ times the incident intensity and $\sim 180$ times for $L = 550$ nm.

Here, we can say that the two resonances at $L = 150$ nm and $L = 550$ nm correspond to an odd half integer multiple of the effective wavelength defined as $\lambda_{\text{eff}} = \lambda_0 / n_{\text{eff}}$, where $\lambda_0$ and $n_{\text{eff}}$ are the free-space wavelength (830 nm) and the effective index of the guided SPP mode of the nanowire, respectively [78]–[80]. For $L = 150$ nm, the first dipolar resonance is at $\lambda_0 = 830$ nm whereas the first dipolar resonance for the 550 nm antenna is at $\lambda_0 \approx 2 \mu$m, and the higher order dipole active mode at $\lambda_0 \approx 830$ nm. Thus, we are exciting the higher order dipolar mode of the 550 nm nanorod antenna when the incident radiation is at the latter wavelength.

The second resonant length is not quite 3 times the first due to the reactance of nanorod ends [80]. $L = 550$ nm resonance yields a lower near-field enhancement than the $L = 150$ nm one since bigger antenna dimensions mean higher radiation and material losses for the same wavelength. When the resonance condition is reached, there is a standing wave optical current distribution present in the nanorod [82]. However, in the full-wave antenna case for $\lambda_{\text{eff}} = 350$ nm, the opposite ends of the nanorod have the same sign of accumulated charges. This yields a very weak dipole and no near-field enhancement at the antenna ends. These nanorod plasmonic antennas exhibit significant field components in all three directions in the near zone, as would be the case near any dipole.

For our purpose, where the intensity enhancement in the near-field matters, both the $\lambda_{\text{eff}}/2$ and the $3\lambda_{\text{eff}}/2$ antennas give similar field distributions at the antenna ends but have different far-field radiation patterns. Since nanorods are inherently elongated with a high-aspect ratio, the quadrupolar contribution is insignificant [57]. The steady-state time-averaged $x$-polarized field amplitude distributions around the nanorod antennas are shown in Fig. 3. The field amplitudes are normalized to the incident plane wave field amplitude.

To investigate coupling effects between nanorods, we studied a pair of gold nanorods on glass substrate separated by a 20 nm gap. When two nanorods are brought together, the near field generated by one will affect the other. This near-field interaction between the pair will change the resonant frequency of the coupled system relative to the isolated nanorod case [73], [82]. In a given nanorod, the near-field generated by the neighboring nanorod counteracts the local electric field induced by the incident field in the nanorod. This will in turn redshift the resonance wavelength [82]. Since the resonance shifts to longer wavelengths with increased near-field coupling, a shorter antenna length compared to an isolated nanorod is needed for resonant enhancement at the wavelength of the single nanorod.

In our simulations for the coupled pair case, we kept all the geometrical parameters constant except for the antenna length. We have calculated the near-field intensity enhancement in the gap as a function of the antenna length. Similar to the single nanorod antenna case, we observed two resonances for antenna lengths between 100 and 700 nm (Fig. 2). The first resonance occurs at $L = 130$ nm and the second at $L = 540$ nm. The enhancement for the first peak is about 800.

The sign of the interaction field between the two nanorods can alternate as a function of the gap between them [82], [83]. When the latter is larger than a quarter of a wavelength, the interaction is mostly due to radiative coupling, and the phase of the radiated field will change as it propagates from one antenna to another [83]. For short enough distances, the near-field interaction dominates and the gap between the nanorods acts as a nanocapacitor with opposite charges on facing antenna ends [62]. Although the field enhancement is mostly in the
antenna gap, there is also significant enhancement at the far ends of the nanorods, as shown in Fig. 4.

Large near-field enhancements [84], [85] are of strong interest for many applications. As shown earlier, one way of getting such intensity enhancements in the near field of metallic particles is to have a pair of nanorods separated by a nanometric gap. The aforementioned capacitor analogy explains this very well as the capacitance is inversely proportional to the gap between the particles. For the case of nearly touching nanorods, one expects huge near-field enhancements [73]. In our antenna design we limit the interparticle gap to 20 nm that is feasible for nanofabrication.

B. Triangular and Bowtie Antennas

Another way of increasing the near-fields is to engineer the antenna terminations and shapes. It is well known in electrostatics that sharp corners concentrate static charges, i.e., the “lightning rod” effect. In this section, we will focus on triangular gold particles that have sharp corners and coupled pairs of these particles so as to increase the near-field enhancement. We studied resonances of 40-nm-thick gold triangular and bowtie antennas on a silica glass substrate. The antennas are illuminated by a plane wave polarized along the x-axis, which has a wavelength of 830 nm. Same boundary conditions as the single nanorod problem are used. The outline of these triangular antennas and their optical near-field intensity enhancement distribution are shown in Fig. 5. The tip radius of curvature for these particles is chosen to be 10 nm and the apex angle is 60°.

The solid red curve in Fig. 6 shows the x-polarized near-field intensity enhancement at the apex of triangular antennas as a function of the antenna length L. The peak intensity enhancements occur for $L = 180$ nm and $L = 700$ nm. These two resonances correspond to a near-field enhancement of 530 and 260 at the antenna apex, respectively. The conduction current induced in the metallic antennas by the incident plane wave for these resonances flows from the wide end of the particle toward the apex of the particle, and then vice versa as the incident polarization changes sign during its normal cycle in time. This suggests a dipolar nature for these $L = 180$ nm and $L = 700$ nm resonances. In contrast to the isolated nanorod antenna case, triangular antennas concentrate the electromagnetic energy mostly at the apex of the particle owing to the “lightning rod” effect. The ratio of the near-field intensity on the wide base of the triangle to that at the apex is small, whereas the nanorods provide identical intensity enhancement on both ends of the particle due to their symmetry.

The near-field response curve for the triangular antennas exhibits another feature (solid red curve in Fig. 6); the resonance peaks are broader compared with the nanorods and evolve into shoulders between $L = 250$ and 400 nm as well as between 800 and 900 nm. For these length intervals, weak quadrupolar resonances become more pronounced since the size of the triangular particle in both x- and y-directions is comparable to the wavelength of incident light [86], [87]. These quadrupolar modes have significant near-field enhancement around the edges of the particle as the induced current flows from one edge to the other.

Bowtie antennas, namely a pair of coupled triangular gold particles, offer higher near-field enhancements and better...
spatial confinement. When two triangular particles are placed side by side with the apices facing one another, the capacitive coupling between them will generate even higher fields than those generated by an isolated particle. The blue curve of Fig. 5 shows how the near-field intensity enhancement in the gap of a bowtie antenna varies as the length of the antenna is increased. There are four discernible features in this curve. For \( L = 140 \) nm and \( L = 660 \) nm, the enhancement is 1200 and 700, respectively. These are the dipolar resonances and their resonant lengths are slightly shorter than those of the isolated triangle. This is consistent with the expected redshift when the near field of the pair is coupled capacitively via the gap. The peaks at \( L = 360 \) nm and \( L = 860 \) nm originate from the quadrupolar resonances of the isolated triangular antenna.

Compared to the other antenna designs, bowties seem to offer the largest near-field enhancements and the smallest spatial extent for the field, i.e., a single sharp optical spot. As shown in Fig. 6, most of the electromagnetic energy is localized in the gap of the bowtie unlike the coupled nanorods where there is significant field enhancement on the far ends. This property of bowties is crucial for applications requiring a very intense spatially confined optical spot.

### III. PLASMONIC LASER ANTENNAS

#### A. Near-Infrared Antennas

Recently, active optical devices that can generate a subwavelength optical spot have been of interest for various applications. Very small aperture lasers that consist of a laser diode with its facet coated by a metal film on which a subwavelength aperture is etched by focused ion beam (FIB) milling have been demonstrated [47]. Panasonic, Inc., has introduced a vertical cavity surface-emitting laser (VCSEL) based on a “SP mirror,” namely, a silver nanohole array [88]. However, these devices suffer from limited throughput even though the transmission is enhanced when normalized to the aperture area [89], [90].

A C-aperture design has also been utilized [49]–[54]. The C-aperture offers several orders of magnitude higher power transmission compared to a square or circular aperture [54]. When a C-aperture is used to achieve a small optical spot in its near field, which requires an aperture area much smaller than the wavelength of light, its throughput is still not substantial.

In this section, we discuss a photonic device, the plasmonic laser antenna, which consists of a resonant optical antenna integrated on the facet of a laser diode [91]. This device relies on the localized SP resonances of the optical antenna that yields large localized near-field enhancements rather than an aperture that offers limited transmission. Such a compact laser source with subwavelength spatial resolution provides distinct advantages in a number of applications including microscopy, spectroscopy, optical data storage, lithography, and laser processing. A schematic of the device is shown in Fig. 7. A bowtie antenna or a pair of coupled nanorods separated by a very small gap, which is less than 30 nm in this paper, is defined on one of the facets of a diode laser by FIB milling. Since the output of the laser diode is polarized parallel to the quantum wells, the optical antenna was oriented accordingly to achieve resonant excitation of SP in the nanorods. The large field enhancement in these structures, compared to that of gold nanospheres, is due to the substantially reduced SP losses, an effect caused by the suppression of interband damping at near-infrared wavelengths [92].

In plasmonic laser antennas, the size of the intense optical spot is largely determined by the size of the gap; a major advantage of this scheme is that it does not suffer from limited throughput as no subwavelength apertures are involved. With an aperture, the size of the optical spot can be equally small, but the power that can be transmitted through such a small subwavelength aperture in a perfect metal will decay as the fourth power of the aperture diameter when the latter is smaller than one-quarter of the illumination wavelength [89].

We modeled optical antennas on alumina substrate in the same fashion as the work described in the previous section. The antennas consist of a pair of gold nanorods separated by a 20 nm gap. For a design wavelength of 830 nm, we determined the resonant antenna lengths for gold nanorods having a 50 nm \( \times \) 50 nm square cross section and a bulk index of refraction of 1.188 + 0.39j [76].

Our calculations indicate that the near-field intensity enhancement in the gap peaks at a value ~800 for an antenna arm length of 130 nm. The nanorod edges are rounded off so as to mimic the fabricated structures (Fig. 8). This length corresponds to the first dipolar mode of this geometry. For this first resonance, the steady-state time-averaged total electric field intensity distribution is very similar to that in Fig. 4. Also, the incident plane wave illumination is polarized along the antenna length.

We fabricated an optical antenna structure that comprises a pair of gold nanorods on a facet of a commercial edge-emitting laser diode (Sanyo, Inc.) operating at a wavelength of 830 nm [91]. This laser package incorporates a photodiode to monitor the laser power emerging from the back facet. First, we deposited a 280-nm-thick alumina insulating layer onto the laser facet in an electron-beam evaporator so as to prevent electrical shorting of the laser and the monitor photodiode in the laser package. A gold layer was then electron-beam evaporated in a custom-made high-vacuum-evaporation system onto the alumina film. This high-vacuum electron-beam evaporation and the evaporation
Fig. 8. (a) AFM topography of the fabricated nanorod optical antenna. (b) SEM image of the same structure.

Fig. 9. Experimental setup used for measuring optical near fields on the facet of near-infrared laser diodes.

Fig. 10. SP holography image on the facet of a semiconductor laser. Inset shows the SEM picture of the 250 nm circular aperture etched into the 100-nm-thick gold layer on the laser facet.

rate are very important for nanofabrication of the antenna as they strongly affect the grain sizes in the evaporated polycrystalline film, which will eventually determine the minimum gap and the roughness in our structures. Next, the optical antenna was defined by direct-write ion beam lithography using a dualbeam FIB microscope (FEI DB235) equipped with a gallium-based liquid metal ion source. The fabricated structure turned out to have a gap of 30 nm. Each nanorod is \( \approx 130 \text{ nm} \) long, \( \approx 50 \text{ nm} \) wide, and \( \approx 50 \text{ nm} \) thick (Fig. 8).

Mapping the optical near-field distribution in the fabricated devices requires a scanning near-field optical microscope. Aper- tureless near-field scanning optical microscopy (a-NSOM) has previously been utilized to study the optical near fields of sub- wavelength apertures of various shapes fabricated on a laser diode [93]. We employ an a-NSOM setup in a similar fashion as shown in Fig. 9. In this technique, a sharp gold-coated atomic force microscope (AFM) tip with a typical radius of curvature of \( \sim 20 \text{ nm} \) scatters the light from the near field as it scans over the sample [94]–[97]. The evanescent fields excite SPs in the tip while the tip is in close proximity to the antenna gap. The gold-coated AFM tip can be modeled as a dipole interacting with its image in the underlying material [96]. A dither piezo drives the AFM cantilever at its resonant oscillation frequency, and when the AFM tip approaches the sample surface in tapping mode, the light scattered by the tip is collected by the back-facet photodiode. The scattered light component modulated at the cantilever oscillation frequency is extracted by means of lock-in detection. When recorded as a function of the cantilever position, the resulting signal gives a map of the optical near-field intensity. Harmonic detection is not necessary for this geometry since the photodiode collects the light primarily scattered back through the laser facet. Lock-in detection at the tip resonant frequency and its second harmonic generated similar images but the former yields a superior SNRs.

The near-field imaging technique used here is sensitive to the light polarized along the height of the pyramidal AFM tip [97]. In conventional AFMs, the cantilever is mounted at a tilt, and therefore, scatters out a combination of all \( x \), \( y \), and \( z \) components of the electric field with weights that are difficult to determine. Another point worth mentioning is that the metallic tip used in the experiments influences the near-field distribution by modifying the nanorod antenna resonance as it oscillates in the proximity of the structure. A change in the gap between the tip and the nanoantenna is reminiscent of a change in capacitance in a resistive-inductive-capacitive (RLC) circuit that affects its resonant frequency. Although these limitations make it difficult to quantify the near-field enhancement in the antenna gap based on near-field measurements, the latter still provide qualitatively the near-field distribution of the nanostructure under study.

This makes a direct comparison between the simulations and the experiments difficult.

In order to check that our near-field imaging setup works as expected, we fabricated a test sample. Our test sample has, instead of a pair of gold nanorods, a circular aperture of 250 nm diameter etched on the facet of one of the laser diodes prepared for antenna fabrication (Fig. 10, inset). With a subwavelength aperture on its facet, the laser diode excites the propagating SPs on the top gold–air interface due to scattering from the sharp edges of this aperture. The measured optical near field in an \( 3.6 \mu\text{m} \times 3.6 \mu\text{m} \) area for this test device is shown in Fig. 10. The near field exhibits standing SP waves instead of propagating ones. This may look surprising at the first glance; however, this can easily be elucidated by considering the interference of the propagating SP waves with the light transmitted directly through the gold film [98]–[100]. There is a small power transmission even when the gold layer is several times thicker than the skin depth of the metal. Due to this interference effect, an
SP hologram is formed on the top gold surface analogous to conventional holography.

The intensity of SPs dies off as they propagate farther away from the aperture. Another distinct feature of SPs is that they have strong longitudinal field components along their propagation direction. Fig. 10 also exhibits this property since the SPs fan out primarily in the horizontal direction, which is the same as the laser polarization.

After verifying that our NSOM setup functioned correctly, we imaged the near field of plasmonic laser antennas using the setup of Fig. 9. Far-field optical power levels up to 30 mW can be achieved with the particular type of commercial laser diode we used. This is well above the damage threshold of gold for continuous wave operation. Thus, the laser was operated at a low duty cycle with a pulse length of 20 ns and a repetition rate of 2 MHz in order to minimize heating effects. We biased the diode with the antenna integrated on its facet to emit into the far-field 0.3 mW optical power with a 4% duty cycle. This corresponds to a pulse peak power of 7.5 mW. A metalized silicon tapping mode AFM cantilever (Budget Sensors-Tap300GB) is used in noncontact mode with the surface, where it is modulated at its resonant frequency around 300 kHz while the sample is scanned underneath it. The near field of the plasmonic antenna is scattered by the metalized AFM tip as it is raster scanned; while this radiation reaches the monitor photodiode predominantly back through the laser diode, a fraction of it is also collected by repeated scattering off the cantilever. In this typical a-NSOM mode, we can record the optical near-field intensity distribution simultaneously with the surface topography. The photocurrent from the backside monitor photodiode is then amplified and fed into a high-frequency digital lock-in amplifier where a phase sensitive measurement is performed using as a reference the frequency of the AFM cantilever.

Results of our NSOM measurements are displayed in Fig. 11. We determine the full-width at half-maximum of the central peak of the near-field intensity distribution to be 40 nm in the x-direction and 100 nm in the y-direction. Our device is capable of generating an intense optical spot that is localized within an area that is 50 times smaller than what one would obtain with conventional diffraction limited optics such as lenses. This is in addition to the large intensity enhancement that also occurs as predicted by the FDTD simulations.

No intensity enhancement was observed in the gap with antenna structures having the same geometrical parameters but fabricated such that the incident is light polarized perpendicular to the antenna length.

As predicted by our simulations, the fabricated antenna also exhibits field enhancement on the far ends of the nanorods. Multiple spatial peaks around the structure are not desired for some applications such as optical data storage where a single optical spot is necessary. By employing a bowtie antenna design, this limitation can be overcome. The small bump seen in the AFM image in Fig. 8(a), below the right-hand side nanorod, is most likely due to nanomasking during FIB patterning, which causes stray near fields in Fig. 11(a) and (b). It is likely that the composition of this bump has changed due to doping by Ga ions used in our FIB system, and this may be the reason why the near field is perturbed strongly as if this bump acts like a metallic nanoparticle. Since we can only measure the near-field intensity distribution qualitatively due to lack of any interferometric background subtraction, we can only provide an estimate of the actual near-field intensity in the gap. Based on the simulated intensity enhancement of 800, an average optical power of 0.3 mW, as used in the experiments, leads to peak intensity of approximately 1 GW/cm² in the gap. This corresponds to an electric field of 10⁹ V/cm at 10 nm above the surface, where the total intensity drops to 20% of its value at the level of the antenna surface. However, because of the influence of the scanning tip, surface roughness, and other factors, it is likely that the field in the gap is somewhat lower than the aforementioned calculated value. Such large localized optical intensities are very important for single molecule SERS.

An interesting question is the role that the antenna can have on the operation of the laser. The area of the antenna is less than one-tenth of the estimated size of the mode on the laser facet and the optical antenna radiates in all directions. Thus, backward reflection from the antenna into the laser is greatly reduced and does not significantly affect its operation. Indeed, no instabilities were detected in the measured optical power. The laser threshold current was measured to be 17 mA whereas the threshold was 25 mA for the pristine laser. After removing the optical antenna by FIB milling, we verified that the threshold current remained at 17 mA. This explains that the reduced laser threshold is indeed due to the gold layer on the laser facet rather than scattering from the antenna.

**B. Mid-IR Antennas**

We have extended our research to mid-IR wavelengths, since a compact coherent radiation source that provides a subwavelength optical spot would be significant for resolving nanometric features of biological and chemical specimens in the “fingerprint region” and for performing absorption spectroscopy with high-spatial resolution [101]. Diffraction-limited mid-IR imaging systems such as Fourier transform infrared (FTIR) microscopes...
offer poor spatial resolution around several microns while many interesting features require resolution better than that of the FTIR microscope. We have implemented our plasmonic antenna scheme on quantum cascade lasers (QCLs), which are semiconductor mid-IR sources based on optical transitions between quantum-confined states in the conduction band [102]. The mid-IR QCLs have recently achieved a high level of technological maturity providing continuous wave operation with hundreds of milliwatts of output power at and above room temperature with good reliability. The emission wavelength of QCLs can be adjusted continuously from about 3 to 24 μm by tailoring the thickness of the active region quantum well layers, thus covering the entire mid-IR “fingerprint region” [103]. A wide range of spectroscopy-based chemical sensing and trace gas analysis techniques using QCLs have been demonstrated [104].

The FDTD simulations have been carried out for the design of mid-IR antennas with a target resonance wavelength of 7.0 μm. Our simulations indicate that the first resonance occurs at $L \approx 1.3 \mu m$ close to $\lambda/2n_{\text{sub}} = 1.1 \mu m$, where $n_{\text{sub}}$ is the effective refractive index of the underlying substrate. Since $\lambda = 7 \mu m$ is much greater than the thickness of the underlying alumina layer (80 nm) deposited on the semiconductor (QCL facet), $n_{\text{sub}}$, is determined by the refractive index of the semiconductor ($n = 3.3$). Gold behaves like an ideal metal at longer wavelengths; therefore, it is easier to estimate the resonant lengths in the mid-IR where the SP dispersion curve is linear.

We used buried heterostructure (BH) QCL devices lasing around $\lambda = 7.0 \mu m$. Details of BH processing and performance can be found elsewhere [105]–[108]. The voltage–current, light output current characteristics, and spectra of these QCLs are measured before antenna fabrication. These devices have many longitudinal modes centered around 7.0 μm, but this does not affect the antenna performance due to the low quality factor of the antenna resonances.

For near-field measurements on QCLs, we modified our near-IR setup. Since our homemade QCLs do not have a built-in monitor photodiode, the scattered radiation is collected from the side with two ZnSe lenses and focused on a liquid nitrogen cooled mercury–cadmium–telluride (MCT) detector. Then, the photocurrent from the MCT detector is demodulated at twice the resonant frequency of the AFM cantilever as suggested by early work on a-NSOM [96].

We first performed NSOM studies on pristine QCLs to measure the mode profiles.

In doing so, we could position the mid-IR antennas accurately on the mode maxima. Before mode characterization, we marked the active region using FIB milling since otherwise we would get a flat AFM topography from the atomically flat cleaved laser facet [Fig. 13(a)]. Our lasers with narrow ridges operate on a single TM$_{00}$ mode as verified by NSOM measurements shown in Fig. 13(b).

After these initial characterization steps, we deposited a 70-nm-thick alumina insulating layer followed by a 70-nm-thick gold layer on the facet of the QCL. Designed antennas that consisted of two rectangular gold stripes separated by a 100 nm gap were then sculpted by FIB milling. The antennas are oriented perpendicular to the quantum well layers since the QCLs are intrinsically TM polarized. During the near-field measurements, the QCL was operated 50% above the threshold current with a 1% duty cycle in pulsed mode. The AFM cantilevers oscillating at 40 kHz scattered mid-IR radiation from the vicinity...
Fig. 14. (a) AFM topography of the fabricated bowtie antenna on the facet of a $\lambda = 7.0 \mu m$ QCL. (b) Near-field map of the bowtie antenna. (c) Linescan along the antenna axis of the near field in (b).

Our results reveal that the optical power in the near field is mostly confined to an $100 \text{ nm} \times 70 \text{ nm}$ area defined by the antenna gap. For our 7.0 $\mu m$ QCL operating at an average power level of 0.1 mW and a calculated field enhancement of 43, we estimate the electric field in the gap to be about $6 \times 10^5 \text{ V/cm}$.

As expected with nanorod antennas, the near-field enhancement on the far ends is about half that in the gap [Fig. 13(d)]. This compact device provides a spatial resolution of $\lambda / 70$ defined by the antenna gap at a wavelength of 7 $\mu m$.

The proposed plasmonic device relies on plasmon resonances of arrays of gold nanoparticles. Before the fabrication of the actual device, we carried out a systematic study of the resonances of coupled gold nanorod arrays on a planar glass substrate in order to determine how their resonance depends on the nanorod length, array spacing, and the local environment. Gold nanorod arrays ($100 \mu m \times 100 \mu m$) of varying nanorod length and rod-to-rod coupling distance were fabricated on indium titanium oxide (ITO) coated glass slides (Sigma-Aldrich). The slides were spin coated with polymethyl methacrylate (PMMA), and then, the arrays were defined using electron-beam lithography. The lithography was followed by electron-beam evaporation of a 3 nm titanium adhesion layer and a 50 nm gold layer. A standard lift-off process removed excess metal and left the desired nanorod arrays [Fig. 16(a)].

We measured the reflection spectrum of the arrays in order to determine the array resonances. In our reflection measurement setup, the nanorod arrays were illuminated with a fiber coupled white light source. The white light was collimated and polarized along the nanorods using a broadband Glan–Thompson polarizer before going through a 50× microscope objective (Mitutoyo, infinity corrected, NA = 0.55, working distance = 13 mm), which focused the light on the sample. The reflected
light was collected back through the same microscope objective and into a fiber coupled spectrometer. For a reflection reference, a reflection spectrum was taken from a silver mirror inserted in place of the sample. Background light was measured and subtracted from our spectra.

The nanorods in the first set of arrays that we used for investigating the coupling between nanorods in the direction along their short axis were approximately 80 nm long and 40 nm wide. The X-gaps between the nanorods were chosen to be approximately 20, 50, 100, and 200 nm, while the gap along their long axis Y-gap was approximately 40 nm. Light was polarized along the nanorods. Fig. 16(b) shows the redshift that was observed in the measured resonance frequency as the X-gap was increased. An array with gaps of 20 nm exhibited a resonance at 606 nm, while one with 200 nm gaps was resonant at 653 nm. For this particular configuration in the near-field coupling regime, the restoring force acting on electrons in a nanorod of the array due to adjacent nanorods adds up constructively with the intrarod restoring force. As the gap is increased, the contribution due to other nanorods decreases resulting in a redshift of the plasmon resonance.

The second set of arrays that we studied consists of nanorods approximately 60 nm wide and 140 nm long. Gaps between the rods in the direction along the rod’s long axis Y-gaps were approximately 20, 50, 100, and 400 nm, whereas the X-gaps were fixed at approximately 120 nm. Fig. 16(c) shows that as the gap between the rods was increased from 20 to 100 nm, the resonance of the arrays blueshifted from 740 nm to 693 nm. For the 400 nm case, there is a redshift instead due to radiative coupling between the nanorods. For distances larger than 100 nm, the near-field interaction is negligible and each nanorod acts as a radiating dipole antenna. The sign of the force acting on electrons in a given antenna due to the radiation from the other nanorods in the array will change sign depending on the distance between them. This accounts for the observed redshift in the 400 nm case.

We also analyzed the dependence of the arrays resonances on the nanorod antenna length. The fabricated nanorods were 40 nm wide and varied in length from approximately 80 to 120 nm in steps of 10 nm. The gap along the nanorods X- and Y-gaps were kept constant at approximately 310 nm and approximately 30 nm, respectively. As we increased the rod length, we observed a monotonic redshift in the resonance wavelength. As shown in Fig. 16(d), the difference in resonance wavelength between the 80- and 120-nm-long rods was 138 nm. This redshift is accounted for by the fact that it takes a longer time for the electrons to traverse a longer nanorod, yielding a lower resonance frequency, and therefore, a longer wavelength.

The effects of local index changes were also investigated by immersing our arrays in various index-matching fluids. The measured resonances undergo a redshift as the index surrounding them is increased since the restoring force acting on the electrons in the nanorod is decreased, thus lowering the plasmon resonance frequency. Without any index fluid, the resonance peaked at a wavelength of 670 nm, and it shifted to 709 and 728 nm when immersed in index-matching fluid with indexes 1.35 and 1.46, respectively [Fig. 16(e)]. Spectra shown were taken immediately after the index-matching fluids were added. Additional reflection measurements were taken after the index fluid was allowed to dry. These resonances had increased amplitude, but their peak resonance wavelengths were unchanged from those shown here.

Due to the broadening of the localized SP resonance of coupled gold nanorods, this type of structure will have limited use for sensing very small local index changes, e.g., 10⁻³ as in the case of molecular binding. Commercially available systems based on SP resonance can detect that small a change in the local environment [56].

All our experimental results are confirmed qualitatively by FDTD simulations. These simulations estimate the near-field intensity enhancement in the gaps to be several hundreds. Each one of these gaps would act like a “hot spot” when the SPs of the array are excited resonantly.

After these theoretical and experimental studies of nanorod arrays on planar glass substrates, we believe that a fiber device based on plasmonic resonances of gold nanorod arrays promises for some applications. We developed a technique to incorporate nanorod arrays on the facet of an optical fiber. A pristine optical fiber was cleaved so as to reveal its clean facet and mounted on a special custom-made fiber holder. Secondly, a 3 nm titanium adhesion layer followed by a 35 nm gold layer was electron-beam evaporated on the fiber facet. We then selectively sculpted, using our FIB system, the fiber facet coated in gold leaving behind arrays of gold nanorods as shown in Fig. 15(b). We positioned our arrays to cover the entire fiber core in order to maximize the interaction area between the light travelling down the fiber and the antenna array. The fabricated array covers a 62.5 \( \mu \text{m} \times 62.5 \ \text{\mu m} \) and comprises nanorods with a cross section separated by roughly 30 nm.
gaps. We were not able to measure the resonances with the fiber device due to heavy gallium ion doping, which causes strong absorption around visible wavelengths unlike the plasmonic laser antennas operating at near-IR and mid-IR frequencies. We are currently working on an alternative fabrication method that utilizes an evaporative electron-beam resist. The recently reported electron-beam assisted deposition of plasmonic nanostructures could also be an alternative approach [111].

V. CONCLUSION

We studied by means of the FDTD simulations the resonant near-field enhancement in single and pair of gold nanorod antennas. The single nanorod geometry has two dipolar resonances that generate large near-field enhancements. When two of these nanorods were separated by a nanometric gap, the resonance antenna length shifted to shorter values due to the capacitive coupling between the nanorods. For a gap of 20 nm, the field enhancement in the gap was roughly 800. The FDTD simulations revealed that the “lighting rod” effect in a triangular gold particle generates higher near-field enhancements and more localized fields compared to the nanorod antennas. A pair of triangular antennas or bowtie antennas represents the best choice for near-field devices.

We successfully fabricated near-IR plasmonic laser antennas that incorporate a coupled gold nanorod antenna on a diode laser facet and demonstrated the field confinement. Our device can be potentially useful in a broad range of applications including optical data storage exceeding that of current highest density digital versatile disks, orders of magnitude higher than the current highest density digital versatile disks, as well as spatially resolved chemical imaging and spectroscopy.

We extended our work on plasmonic antenna to QCLs in the mid-IR regime. We demonstrated a resolution of $\lambda/70$ for a wavelength of 7.0 $\mu$m. If this device is used as an active NSOM scan head, it can potentially outperform the FTIR microscopes that offer diffraction limited resolution.

Fiber devices that incorporate coupled gold nanorod arrays were also proposed and fabricated. We experimentally and theoretically studied the resonances of nanorod arrays on glass slides that will be integrated onto the fiber facet. This fiber device can be used as a modular SERS probe and sensor that detects local index changes around the gold arrays.

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