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Design and Analysis of a Graphene Based Slotted Bowtie Optical Plasmonic Nanoantenna

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Abstract

A graphene-based modified bowtie plasmonic nanoantenna resonating in the optical frequency spectrum with the periodic directors created by the slots on top of the radiating structure has been proposed in this paper. In the field of nanophotonics, a few optical nanoantennas have been reported to construct multipath wireless nanolinks. At the telecommunication wavelength of 1550 nm (193.5 THz), the maximum directivity of 9.67 dBi has been reached due to the maximum absorption power of graphene sheet by selecting the chemical potential of 0.5 eV. Since graphene supports surface plasmon polariton waves and acts either as an absorptive or transparent medium for distinct chemical potentials, the proposed graphene-based slotted bowtie optical nanoantenna has been optimized to obtain a dynamically controlled triple-directional radiation beam. With this distinctive nature, a multipath intra or inter on-chip wireless nanolink for secure optical data transfer can be realized by integrating a set of our proposed optical plasmonic nanoantennas.

Keywords *Graphene, Optical frequency spectrum, Surface plasmon polariton, Wireless optical nanolink*

Introduction

Plasmonic optical nano-scale antennas radiating multiple beams have drawn recently so much interest of the current nanophotonic research community that researchers are persistently attempting to construct innovative optical nanostructures which effectively link the localized energy of confined light in the subwavelength volume and free space radiation [1-4]. Sensing [5, 6], spectroscopy [7, 8], nanophotonic circuitry [9-13], improved photoemission and photodetection [14-18], nonlinear optics [19, 20] and optical metasurfaces [21, 22] are some of the emerging applications where the optical nanoantennas are being extensively integrated because of their exceptional control over electromagnetic field which yields highly oriented radiation pattern, nominal power consumption and better impedance matching. However, unlike the typical microwave and radio frequency antennas, optical plasmonic nanoantennas cannot radiate beams over a long distance due to the intrinsic ohmic losses of metals at optical regime [31, 32].

The formation of an optical wireless communication link is possible once the radiating portions of the optical multibeam nanoantennas can accept an optical signal in-plane and to emanate multiple beams simultaneously towards several directions in the free space using the reciprocity theorem [62]; graphene layers regulated by electrostatic gate bias voltage are sandwiched by other material layers such that more directive radiation patterns are apparent [23-30]. By applying a group of plasmonic multibeam optical nanoantennas as an intra or inter on-chip wireless nanolink in the photonic integrated circuits (PICs) [33, 34], the transmission of data from one device located at one chip to other devices at several layers is inevitable [35, 36].

At the outset, Alù and Engheta proposed a set of complemented dipole nanoantennas in order to construct an optical wireless nanolink which demonstrated notable performance and negligible impedance mismatch losses as compared to its wired counterpart [10]. In earlier studies on the optical wireless nanolinks, some other variants of optical nanoantennas were introduced, for instance, graphene patch [37], Yagi-Uda [38], circular hybrid plasmonic [33], phase array [39], dipole-loop [40], and cross dipole [41] nanoantennas.

In this paper, a graphene based slotted bowtie optical nanoantenna radiating triple-directional (TD) beams with a high directivity of 9.67 dBi at 193.5 THz (wavelength of 1550 nm) has been proposed for the very first time. With the appropriate electrostatic biasing or chemical doping in graphene sheet [42, 43], the chemical potential of graphene changes. The conductivity of graphene has been altered by means of the variation of chemical potential such that the overall radiating structure absorbs the maximum incident power at the wavelength of 1550 nm. Directors composed of silver, graphene and SiO₂ in the slotted bowtie radiating structure further result in the return loss as low as -23.089 dB, VSWR of 1.151, high gain of 7.38 dB, and satisfactory radiation efficiency of 76.32%. Therefore, this proposed optical plasmonic nanoantenna possessing excellent directivity is conceivably an alternative to realize the multipath point-to-point wireless nanolinks.

Graphene-Based Slotted Bowtie Optical Plasmonic Nanoantenna Design

Surface Plasmon Polariton, Plasmonic Resonance & Dispersion Relation of Graphene

The dispersion relation of the supported transverse magnetic (TM) plasmons or the SPP wave vector (k_{SPP}) in a free space standing graphene sheet of conductivity (σ_g) can be represented as [44-46]

$$k_{SPP} = k_0 \sqrt{1 - \left(\frac{2}{\eta_{eff}\sigma_g}\right)^2} \approx \frac{\hbar\omega^2}{2\alpha\mu_c c} \quad (1)$$

$$\eta_{eff} = \sqrt{1 - \frac{4\mu_0}{\epsilon_0(\sigma_g)^2}} = \frac{\lambda}{\lambda_{SPP}} \quad (2)$$

where the complex conductivity (σ_g) of graphene is a function of chemical potential (μ_c) or Fermi energy (E_f), charge particle scattering rate or reflection efficient (Γ), relaxation time (τ), angular frequency ($\omega = 2\pi f_r$), and temperature (T). k_0 and η_{eff} are the free-space wavenumber and effective intrinsic impedance or mode index of graphene sheet, respectively. In free space, η_{eff} is related to both the permeability (μ_0) and the absolute permittivity (ϵ_0) of graphene as shown in Eq. (2) [47].

Another way of determining the k_{SPP} is to vary the chemical potential by applying a bias voltage across the graphene nodes. From the dispersion relationship in Eq. (1), it is obvious that k_{SPP} varies as a second order function of the resonant frequency while assuming other parameters constant. The constants are as follows: the reduced plank's constant ($\hbar$), the fine structure constant ($\alpha = \frac{e^2}{\hbar c} \frac{1}{4\pi\epsilon_0} = \frac{1}{137}$) [48], the charge of electrons (e) and the velocity of light in vacuum (c).

$$L_g = m \frac{\lambda}{2\eta_{eff}} = m \frac{\lambda_{SPP}}{2} = m \frac{\pi}{k_{SPP}} \quad (3)$$

Plasmonic resonances of SPP waves helps evaluating the length of the graphene layers (L_g) [49]. In Eq. (3), m is an integer number of resonant modes, λ defines the wavelength of the incoming radiation through the discrete port, and λ_{SPP} expresses the wavelength of SPP waves.

$$L_g = m \frac{2\pi\alpha\mu_c c}{\hbar\omega^2} \quad (4)$$

$$f_r = \sqrt{m \frac{\alpha\mu_c c}{2\pi L_g \hbar}} \quad (5)$$

Replacing the SPP wave vector in Eq. (3) with its expression from Eq. (1) results in L_g which is a function of resonant frequency (f_r) exhibited in Eq. (5). Therefore, for a lower application specific f_r , the length of the graphene layers should be increased.

Conductivity, Surface Impedance, Power Absorption of Graphene

According to the Kubo formula [50], $\sigma_g(\omega, \mu, \Gamma, T)$ is a combination of both inter-band and intra-band transitions as expressed in Eq. (6). From Eq. (9), the characteristic impedance of the supported

transverse magnetic (TM) plasmons in the graphene sheet can be computed as [44-46], where R_g and X_g are the surface resistance and reactance of the graphene sheet, correspondingly; $\epsilon_{r(eff)}$ is the effective dielectric constant of the surrounding media.

$$\sigma_g = \sigma_{intra} + \sigma_{inter} \quad (6)$$

$$\sigma_{intra}(\omega, \mu, \Gamma, T) = -j \frac{e^2 K_B T}{\pi \hbar^2 (\omega - j\Gamma)} \left\{ \frac{\mu_c}{K_B T} + 2 \ln \left(e^{-\frac{\mu}{K_B T}} + 1 \right) \right\} \quad (7)$$

$$\sigma_{inter}(\omega, \mu, \Gamma, T) = \frac{-j e^2}{4 \pi \hbar^2} \ln \left(\frac{2|\mu_c| - (\omega - j\Gamma)\hbar}{2|\mu_c| + (\omega - j\Gamma)\hbar} \right) \quad (8)$$

$$Z_g = Z_c = \frac{1}{\sigma_g} = R_g + jX_g = \frac{k_{SPP}}{\omega \epsilon_0 \epsilon_{r(eff)}} \quad (9)$$

There is a strong relationship between the chemical potential (μ_c) and the electrostatic biasing gate voltage (V_g), which is as follows [51]

$$\mu_c = E_f = \hbar v_f \sqrt{\frac{\pi \epsilon_{ox} \epsilon_0 V_g}{e t_{ox}}} = \hbar v_f \sqrt{\frac{\pi C_{ox} V_g}{e}} \approx \hbar v_f \sqrt{\pi N} \quad (10)$$

where v_f is the velocity of electrons in Fermi energy level ($\approx 10^6 \text{ ms}^{-1}$), ϵ_{ox} is the permittivity of SiO₂ layer, t_{ox} is the oxide thickness, $C_{ox} (= \frac{\epsilon_{ox} \epsilon_0}{t_{ox}})$ is the electrostatic gate capacitance/area, and N ($\approx \frac{C_{ox} V_g}{e}$) is the carrier concentration [52]. It is evident from Eq. (10) that the more is the biasing voltage, the more is the chemical potential.

One of the characteristics of graphene is the relaxation time during which it retrieves a uniform charge density after a biasing voltage is introduced and it is given by [53]

$$\tau \approx \mu_c \hbar \sqrt{\frac{\pi N}{e v_f}} \quad (11)$$

In order to increase the conductivity of graphene, the relaxation time has to be improved to at least 0.1 ps by enhancing the chemical potential, referring to Eqs. (6-8, 11).

Graphene Modelling

The evaluation of the absorbed power of graphene at 1550 nm as per Eq. (13) is crucial to analyze the epsilon-near-zero effect of graphene. Based upon the electrostatic gate bias which controls the chemical potential (μ_c), such effect of graphene is likely to be modified [55].

$$\epsilon_g(\omega, \mu, \Gamma, T, \Delta) = 1 + \frac{j \sigma_g}{\omega \epsilon_0 \Delta} \quad (12)$$

$$\begin{aligned} \text{Power} &\propto \frac{\text{Energy}^2}{\text{Impedance}} \propto \text{Conductance} \times \text{Energy}^2 \\ &\propto \text{Conductance} \times (\text{Charge} \times \text{Voltage Difference})^2 \end{aligned}$$

$$P_g = \frac{Re(\sigma_g)E^2}{2} \quad (13)$$

By tuning the chemical potential (μ_c) which in turn changes the conductivity (σ_g) and considering charge particle scattering rate (Γ) to be 0.00051423 eV, the dielectric function of graphene (ϵ_g) with a thickness of $\Delta = 0.34$ nm is attained, leading to a reconfigurable plasmonic device as specified by Eq. (12) [54]. Such a device is prone to absorb low and high powers (P_g) only by altering its conductivity and adjusting the incident laser photon energy (E), which is indicated evidently in Eq. (13) [55].

Using the Ansys Lumerical software based upon finite-difference time-domain method (FDTD), the relationship among chemical potential, frequency and conductivity of graphene material has been extracted analytically. A proportional relationship of the real and imaginary parts of σ_g with μ_c is depicted in Figure 1.

Fig. 1 Change in real and imaginary parts of conductivity curves of graphene with respect to chemical potentials (μ_c) ranges from 0 eV to 1 eV for $\tau = 0.1$ ps at $f_r = 193.5$ THz and $T = 300$ K

Despite both parts of conductivity of graphene for $\mu_c = 0.0$ eV have the proportional relationship with frequency (190 – 195 THz) as shown in Fig. (2), a negative correlation between the imaginary part of the conductivity and frequency is apparent for $\mu_c = 0.5$ eV; on the other hand, $Re(\sigma_g)$ increases with the rise of frequency for $\mu_c = 0.5$ eV as presented in Fig. (3). At $f_r = 193.5$ THz, the real parts of graphene conductivity, $Re(\sigma_g)$, decline with the improvement of chemical potential; $Re(\sigma_g)$ nearly equals 60.85 μS and 1.43 μS for $\mu_c = 0$ eV and 0.5 eV, respectively. In contrast, $Im(\sigma_g) \approx -0.04$ μS and $Im(\sigma_g) \approx 3.3$ μS for $\mu_c = 0$ eV and 0.5 eV, individually.

Fig. 2 Change in real ($\text{Re}(\sigma)$) and imaginary ($\text{Im}(\sigma)$) parts of conductivity curves of graphene as functions of frequency (190 THz – 195 THz) for $\mu_c = 0.0$ eV and $\tau = 0.1$ ps and $T = 300$ K

Fig. 3 Change in real ($\text{Re}(\sigma)$) and imaginary ($\text{Im}(\sigma)$) parts of conductivity curves of graphene as functions of frequency (190 THz – 195 THz) for $\mu_c = 5$ eV and $\tau = 0.1$ ps and $T = 300$ K

Thus, for $\mu_c = 0$ eV with no bias voltage, graphene acts as a transparent medium. Conversely, graphene behaves as an absorptive medium at 1550 nm for $\mu_c = 0.5$ eV. When $\mu_c < \frac{\hbar\omega}{2}$, the maximum power absorption of graphene can be found where the inter-band contribution dominates.

Nanoantenna Design

Figure (4) shows each modified layer of the Graphene Based Slotted Bowtie Optical Nanoantenna modelled in the finite element method (FEM) simulator called “CST Microwave Studio”, starting with a silver ground plane, and covering by a perturbed graphene structure (in the 2nd last stage). Due to better surface plasmon polaritons (SPPs) excitation of silver (Ag) at low-terahertz and optical regime, Ag has been chosen instead of gold layer. Apart from this nature of Ag, smaller charge particle scattering rate (Γ) of 0.02eV, lower fabrication cost, and lower loss make it an ideal choice for this nanoantenna [57, 58]. Due to this, Ag ground plane is modelled and is followed by a homogenous graphene patch. The homogeneous graphene patch enhances the propagation of SPPs further across the nanoantenna caused by its high carrier mobility, provides optical contrast, and ensures mechanical support to the following slotted bowtie structures [59]. The conventional bowtie structure has more capacitive loading and diffraction limit, offers inadequate output power as a

consequence of thermal breakdown and carrier screening effect within active areas, and provides low quantum efficiency owing to a long carrier transport path to feedline. Several rectangular slots are made over the generic bowtie in order to construct a series of periodic horizontal directors. As compared to the typical bowtie, slotted bowtie with periodic horizontal directors responds rapidly due to the shorter photo-carrier transport path to feedline (exciting more SPPs along the slots) and delivers more directive radiation beam having high output power along z-axis without enhancing the capacitive loading [60]. Therefore, a combination of silica (SiO_2), graphene and Ag materials has been employed to form this slotted bowtie radiating structure which was placed on top of the homogenous graphene patch. In the last stage of Fig 4, our proposed graphene based slotted bowtie optical plasmonic nanoantenna has been demonstrated.

To illuminate the proposed nanoantenna, either a Femto second laser or a quantum dot source is considered, which was represented, in our case, by a discrete port with input power of 1W and internal impedance of 50Ω in CST Microwave Studio [59]. However, for the improvement of device-based quantum network structure, quantum dot source is supposed to be a way through which safe communication in the low-loss optical region about 193.5 THz (1550 nm) is possible [60]. By picking two feed points of top Ag layer, the starting and ending points of the discrete port were specified. In the full form of the proposed nanoantenna as depicted in Figure 4, a blue line connecting the two points and the red cone sitting in the center of the line indicate a perfectly conducting electrical wire and a discrete port source, respectively.

Fig. 4 Modified layers of various materials (Ag, Graphene & SiO_2) to observe the antenna resonance at 193.5THz. Discrete port is an illumination port, resembling the quantum dot or femto second laser source

Fig. 5 3D schematic views of the graphene-based slotted bowtie optical plasmonic nanoantenna. **a** top view. **b** side view

Parametric analysis in CST Microwave Studio paves the path to effectively optimize the nanoantenna at 193.5 THz. The optimized dimensions of several structures of the proposed nanoantenna are illustrated in Fig. (5) and listed in Table 1. The overall length and width of the radiating structure in the nanoantenna are usually selected dynamically based upon the desired resonant frequency as specified in literature [56]. For optical applications (850 nm, 1300 nm, & 1550 nm) e.g., multipath intra or inter on-chip wireless nanolink, each one of the optimized length and width of the radiating portion has been chosen to be 2112 nm and thickness to be 160 nm.

Table 1 Optimized dimensions of the proposed graphene-based slotted bowtie optical plasmonic nanoantenna

Dimension	Values (nm)
Diagonal of slotted bowtie ($D_{bow-tie(slotted)}$)	1423.60
Bottom graphene thickness ($t_{Ag(bottom)}$)	200

Dielectric thickness (t_{ox})	90
Patch of graphene length and width ($L_{g(patch)}$ & $W_{g(patch)}$)	4000 each
Intermediate graphene thickness ($t_{g(int)}$)	10
Top graphene thickness ($t_{g(top)}$)	10
Silver (Ag) ground plane length & width ($L_{Ag(bottom)}$ & $W_{Ag(bottom)}$)	6000 each
Midway Silver (Ag) thickness (t_{Ag})	40
Midway graphene thickness ($t_{g(mid)}$)	10
Radiating structure (Graphene, SiO ₂ , & Ag) length and width (L_{rad} & W_{rad})	2112 each
Gap between slots (G_{slot})	94.91
Gap between feed points (G_{feed})	200

Simulation and Results

Using the time domain solver of CST Microwave Studio, the proposed nanoantenna was designed and simulated successfully. For transient analysis, CST makes use of finite integration technique (FIT). In order to refine the design in CST, hexahedral-type mesh with default automatic mesh adaptation is taken into consideration while performing transient analysis [61].

The return loss of the proposed nanoantenna is a measure of power loss of the reflected wave at the discrete port because of the mismatch from the feed line. Low return loss ($S_{11} < -10$ dB) and low voltage standing wave ratio (VSWR < 2) indicate the parts of nanoantenna are well matched for a frequency of interest. Figure (6) illustrates the return loss (S_{11}), -10 dB impedance bandwidth (BW) and VSWR of -23.089 dB, 2.2964 THz and 1.151, respectively, for the proposed nanoantenna operating at 193.5 THz resonant frequency. The electric field (E-field) pattern along XZ plane and magnetic field (H-field) pattern along YZ plane at 193.5 THz are depicted in Figure 7. From Fig. 7(a), an intense E-field for a phase of 90° is observed at the slant edges of the bowtie directors, which becomes even stronger when it propagates towards the Ag ground plane. At the central region of the bowtie structure and homogenous graphene patch, a high H-field for a phase of 180° is noticed as illustrated in Fig. 7(b).

(a)

(b)

Fig. 6 a. Return Loss (S_{11}) and **b.** VSWR of the proposed optical nanoantenna at 193.5 THz

(a)

(b)

Fig. 7 Plasmonic behavior of the proposed nanoantenna at 193.5 THz in terms of **a.** electric field and **b.** magnetic field

Fig. 8(a) shows 3D far field directivity radiation pattern of the nanoantenna and Fig. 8(b) illustrates E-plane as well as H-plane polar plots for co-polarization and cross polarization with directivity as outcome. It is evident from Fig. 8 that the proposed nanoantenna radiates triple directional electromagnetic waves along z-axis, having maximum directivity of 9.67 dBi and negligible back lobe. At 193.5 THz, the 3 dB angular widths or half power beamwidths (HPBW) for co-polarized E-Plane (θ_E) and H-Plane (θ_H) of the nanoantenna are 28.9° and 45.7° , respectively. On the contrary, the HPBW's for cross-polarized E-Plane (θ_E) and H-Plane (θ_H) of the nanoantenna are 30.5° and 28° , correspondingly. The 3D and 2D radiation patterns for gain of the proposed nanoantenna at 193.5 THz are shown in Figure (9), where the maximum gain of 7.38 dB is attained. From 2D radiation pattern, gain is around azimuth within theta of 30° to just over 60° .

(a)

Fig. 8 Far field directivity radiation pattern of the nanoantenna operating at 193.5 THz. **a** 3D plot **b** Co-polarization of electric and magnetic fields **c** Cross polarization of electric and magnetic fields

(b)

Fig. 9 The **a.** 3D and **b.** 2D radiation pattern for gain of the nanoantenna at 193.5 THz

Table 2 summarizes the prominent features of the proposed graphene based slotted bowtie optical plasmonic nanoantenna and compares the aspects (size, return loss, gain and directivity) of our design with the existing optical nanoantennas. At 1550 nm (193.5 THz), several directors in our proposed design increase the directivity of the triple directional radiation pattern more than 3.67 dBi compared to that of bidirectional radiation beam of the waveguide-fed hybrid plasmonic patch nanoantenna [62]. Again, in comparison to the nanoantenna in Ref. [62], our nanoantenna possesses higher gain (7.38 dB), lower return loss (-23.089 dB) and smaller footprint. In literature [40, 64, 66, 69], the optical nanoantennas resonating at the telecommunication frequencies (193.5 THz & 229 THz) attain return losses greater than -23.089 dB and directivities less than 9.67 dBi; hence, the performance of these nanoantenna is not good enough as opposed to our proposed nano-scale antenna. Although the hybrid plasmonic waveguide fed broadband nanoantenna [63] and the hybrid plasmonic horn nanoantenna [67] have compact radiating structures in contrast to our optical plasmonic nanoantenna, these two hybrid plasmonic nanoantennas provide gains < 7.38 dB and return losses (S_{11}) > -23.089 dB. The footprints of the Yagi-Uda antenna [68] and the array of Yagi-Uda nanoantennas [65] are larger, however the proposed graphene based slotted bowtie optical nanoantenna has achieved lower return loss and better gain compared to the former and latter Yagi-Uda nano-scale structures, respectively.

Table 2 Comparison among earlier related investigations on optical nanoantenna with the proposed design. UD is unidirectional, BD is bidirectional, TD is triple-directional, QD is quad-directional, and N is not mentioned

Reference	Type of Antenna	Footprint (μm^2)	Operating Frequency (f_r) (THz)	S_{11} (dB)	Gain (dB)	Directivity (dBi)
[68]	Yagi-Uda Antenna	10×19.5	193.5	-13.2	12.9	16.6 (UD)
[65]	Yagi-Uda Nanoantenna Array	90×90	193.5	N	6	18 (BD)

[67]	Hybrid Plasmonic Horn Nanoantenna	0.45×0.625	193.5 229 352.9	-15.7 -12.8 -15.6	4.7 7.3 4.8	N (UD)
[63]	Hybrid plasmonic waveguide fed broadband nanoantenna	0.55×0.5	193.5 229	-13 -22	5 4.6	N (UD)
[40]	Cross Dipole Nanoantenna	3.5×3.5	193.5	N	N	8.79 (UD) 8.63 (BD) 8.42 (QD)
[69]	Triangular Patch Nanoantenna	0.55×0.5	193.5 229	-12.86 -13.56	7.792 5.667	8.79 (UD) 6.51 (UD)
[66]	Dielectric Resonator Nanoantenna	5×5	193.5	-22	N	8.6 (UD)
[64]	Hybrid Plasmonic Nanoantenna on InP Substrate	0.7×0.7	193.5	-21	6.6	6.9 (UD)
[62]	Waveguide-fed Hybrid Plasmonic Patch Nanoantenna	5.6×5.6	193.5	-10.56	5.6	6 (BD)
Proposed Antenna	Graphene Based Slotted Bowtie Optical Plasmonic Nanoantenna	2.112×2.112	193.5	-23.089	7.38	9.67 (TD)

Conclusion

In this work, a graphene based slotted bowtie nanoantenna operating in optical regime for the point-to-point wireless nanolink has been theoretically analyzed and simulated using CST Microwave Studio. The peak directivity of the proposed bowtie optical nanoantenna is 9.67 dBi, which is obtained not only due to the inclusion of slots but also the change in chemical potential of graphene sheet by electrical gate bias. The concept of applying slots over the bowtie radiating structure has been considered since each slot creates two directors; Two sets of the left directors and another two sets of counterparts steer the radiation beam in the elevation plane. In terms of securing the optical

data transmission to three inter or intra on-chips at 193.5 THz, the proposed highly directive graphene based slotted bowtie optical plasmonic nanoantenna radiating triple directional beams could be a solution.

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Competing interests

The authors declare no competing interests.

Availability of data and material

Requests for data and relevant materials should be addressed to R.V.B.

Code availability

Not applicable.

Authors' contributions

R.V.B. and F.A. perceived the basic idea for this work. R.V.B. performed the FEM and FDTD simulations, analyzed the data and wrote the paper under the supervision of F.A. All the authors revised the manuscript based on the technical and scientific observations while discussing about the results.

Ethics approval

Not applicable.

Consent to participate

Not applicable.

Consent for publication

Not applicable.

References

1. Meng, Y., Hu, F., Shen, Y. et al. Ultracompact Graphene-Assisted Tunable Waveguide Couplers with High Directivity and Mode Selectivity. *Sci Rep* 8, 13362 (2018). <https://doi.org/10.1038/s41598-018-31555-7>
2. Novotny, L. & van Hulst, N. Antennas for light. *Nature Photonics* 5, 83–90 (2011)

3. Zangari, A., Micheli, D., Galeazzi, R. & Tozzi, A. Node of ranvier as an array of bio-nanoantennas for infrared communication in never tissue. *Sci. Rep.* 8, 539 (2018)
4. Dou, H. et al. 2D large beam inclination angle multibeam array antenna without beamforming network. *Electromagnetics* 39, 453–463 (2019)
5. Law, S., Yu, L., Rosenberg, A. & Wasserman, D. All-semiconductor plasmonic nanoantennas for infrared sensing. *Nano Lett.* 13, 4569–4574 (2013)
6. Liu, N., Tang, M. L., Hentschel, M., Giessen, H. & Alivisatos, A. P. Nanoantenna-enhanced gas sensing in a single tailored nanofocus. *Nature Mater.* 10, 631–636 (2011)
7. Punj, D. et al. A plasmonic ‘antenna-in-box’ platform for enhanced single-molecule analysis at micromolar concentrations. *Nature Nanotech.* 8, 512–516 (2013)
8. Zhang, R. et al. Chemical mapping of a single molecule by plasmon-enhanced Raman scattering. *Nature* 498, 82–86 (2013)
9. Huang, J., Feichtner, T., Biagioni, P. & Hecht, B. Impedance matching and emission properties of nanoantennas in an optical nanocircuit. *Nano Lett.* 9, 1897–1902 (2009)
10. Alù, A. & Engheta, N. Wireless at the nanoscale: optical interconnects using matched nanoantennas. *Phys. Rev. Lett.* 104, 213902 (2010)
11. Dregely, D. et al. Imaging and steering an optical wireless nanoantenna link. *Nature Commun.* 5, 4354 (2014)
12. Solís, D. M., Taboada, J. M., Obelleiro, F. & Landesa, L. Optimization of an optical wireless nanolink using directive nanoantennas. *Opt. Express* 21, 2369–2377 (2013)
13. Akselrod, G. M. et al. Probing the mechanisms of large Purcell enhancement in plasmonic nanoantennas. *Nature Photon.* 8, 835–840 (2014)
14. Guo, R. et al. Plasmonic Fano Nanoantennas for on-chip separation of wavelength-encoded optical signals. *Nano. Lett.* 15, 3324–3328 (2015)
15. Yang, Y., Li, Q. & Qiu, M. Controlling the angular radiation of single emitters using dielectric patch nanoantennas. *Appl. Phys. Lett.* 107, 031109 (2015)
16. Ramaccia, D., Bilotti, F., Toscano, A. & Massaro, A. Efficient and wideband horn nanoantenna. *Opt. Lett.* 36, 1743–1745 (2011)
17. Gurto, A. G. et al. Unidirectional emission of a quantum dot coupled to a nanoantenna. *Science* 329, 930–933 (2010)
18. Yang, Y., Zhao, D., Gong, H., Li, Q. & Qiu, M. Plasmonic sectoral horn nanoantennas. *Opt. Lett.* 39, 3204–3207 (2014)
19. Bar-Lev, D. & Scheuer, J. Efficient second harmonic generation using nonlinear substrates patterned by nano-antenna arrays. *Opt. Express* 21, 29165–29178 (2013)
20. Kauranen, M. & Zayats, A. V. Nonlinear plasmonics. *Nature Photon.* 6, 737–748 (2012)
21. Zhao, H., Yang, Y., Li, Q. & Qiu, M. Sub-wavelength quarter-wave plate based on plasmonic patch antennas. *Appl. Phys. Lett.* 103, 261108 (2013)
22. Kildishev, A. V., Boltasseva, A. & Shalae, V. M. Planar photonics with metasurfaces. *Science* 339, 1232009 (2013)
23. Yang, Y., Li, Q. & Qiu, M. Broadband nanophotonic wireless links and networks using on-chip integrated plasmonic antennas. *Sci Rep* 6, 19490 (2016). <https://doi.org/10.1038/srep19490>
24. Souza, J. L. & Costa, K. Q. Broadband wireless optical nano link composed by dipole-loop nanoantennas. *IEEE Photon. J.* 10, 2200608 (2018)
25. Khodadadi, M. & Nozhat, N. Theoretical analysis of a super-mode waveguide and design of a complementary triangle hybrid plasmonic nano-antenna. *IEEE J. Sel. Top. Quantum Electron.* 27, 4600210 (2021)
26. Castilla, S. et al. Plasmonic antenna coupling to hyperbolic phonon-polaritons for sensitive and fast mid-infrared photodetection with graphene. *Nat. Commun.* 11, 4872 (2020)
27. Rui, G., Abeyasinghe, D. C., Nelson, R. L. & Zhan, Q. Demonstration of beam steering via dipole-coupled plasmonic spiral antenna. *Sci. Rep.* 3, 2237 (2013)
28. Mehta, B., Benkstein, K. D., Semancik, S. & Zaghoul, M. E. Gas sensing with bare and graphene-covered optical nano-antenna structures. *Sci. Rep.* 6, 21287 (2016)
29. Salary, M. M., Forouzmand, A. & Mosallaei, H. Controllable directive radiation from dipole emitter coupled to dielectric nanowire antenna with substrate-mediated tunability. *MRS Commun.* 8, 437–445 (2018)
30. Sallam, M. O., Vandenbosch, G. A. E., Gielen, G. G. & Soliman, E. A. Novel wire-grid nano-antenna array with circularly polarized radiation for wireless optical communication systems. *J. Lightwave Technol.* 35, 4700–4706 (2017)
31. Jia, H., Liu, H. & Zhong, Y. Role of surface plasmon polaritons and other waves in the radiation of resonant optical dipole antennas. *Sci. Rep.* 5, 8456 (2015)

32. Khodadadi, M., Nozhat, N. & Moshiri, S.M.M. Theoretical analysis of a circular hybrid plasmonic waveguide to design a hybrid plasmonic nano-antenna. *Sci Rep* 10, 15122 (2020). <https://doi.org/10.1038/s41598-020-71863-5>
33. Rui, G., Zhan, Q. Highly sensitive beam steering with plasmonic antenna. *Sci Rep* 4, 5962 (2014). <https://doi.org/10.1038/srep05962>
34. Novotny, L. & Hulst, N. V. Antennas for light. *Nat. Phot.* 5, 83–90 (2011)
35. Hong, W. et al. Multibeam antenna technologies for 5G wireless communications. *IEEE Trans. Antennas Propag.* 65, 6231–6249 (2017)
36. Khan, M. A. K., Ullah, M. I., Kabir, R. & Alim, M. A. High-performance graphene patch antenna with superstrate cover for terahertz band application. *Plasmonics* 15, 1719–1727 (2020)
37. Kullock, R., Ochs, M., Grimm, P., Emmerling, M. & Hecht, B. Electrically driven Yagi-Uda antennas for light. *Nat. Commun.* 11, 115 (2020)
38. Zeng, Y. S. et al. All-plasmonic optical phased array integrated on a thin-film platform. *Sci. Rep.* 7, 9959 (2017)
39. J. L. de Souza and K. Q. da Costa, "Broadband Wireless Optical Nanolink Composed by Dipole-Loop Nanoantennas," in *IEEE Photonics Journal*, vol. 10, no. 2, pp. 1–8, April 2018, Art no. 2200608, doi: 10.1109/JPHOT.2018.2810842.
40. Moshiri, S.M.M., Nozhat, N. Smart optical cross dipole nanoantenna with multibeam pattern. *Sci Rep* 11, 5047 (2021). <https://doi.org/10.1038/s41598-021-84495-0>
41. Kwon, S. J. et al. Extremely stable graphene electrodes doped with macromolecular acid. *Nat. Commun.* 9, 2037 (2018)
42. Liatser, I. et al. Graphene-based nano-patch antenna for terahertz radiation. *Photon. Nanostruc. Fundament. Appl.* 10, 353–358 (2012)
43. M. Jablan, H. Buljan, and M. Soljačić, "Plasmonics in graphene at infrared frequencies," *Phys. Rev. B -Condens. Matter Mater. Phys.*, vol. 80, no. 24, p. 245435, Dec. 2009.
44. D. Correas-Serrano, J. S. Gomez-Diaz, J. Perruisseau-Carrier, and A. Alvarez-Melcon, "Spatially dispersive graphene single and parallel plate waveguides: Analysis and circuit model," *IEEE Trans. Microw. Theory Tech.*, vol. 61, no. 12, pp. 4333–4344, Dec. 2013.
45. D. Correas-Serrano, J. S. Gomez-Diaz, J. Perruisseau-Carrier, and A. Alvarez-Melcon, "Graphene-based plasmonic tunable low-pass filters in the terahertz band," *IEEE Trans. Nanotechnol.*, vol. 13, no. 6, pp. 1145–1153, Nov. 2014.
46. Vakil A, Engheta N (2011) Transformation optics using graphene. *Science* 332:1291–1294
47. Nair RR, Blake P, Grigorenko AN, Novoselove KS, Booth TJ, Stauber T, Peres NMR, Geim AK (2008) Fine structure constant defines visual transparency of graphene. *Science* 320:1308
48. Cubukcu E, Capasso F (2009) Optical nano rod antennas as dispersive one-dimensional Fabry–Pérot resonators for surface plasmons. *Appl Phys Lett* 95:201101
49. Gusynin V, Sharapov S, Carbotte J (2006) Magneto-optical conductivity in graphene. *J Phys Condens Matter* 19(1–28):026222
50. Zeng, C., Liu, X., Wang, G.: 'Electrically tunable graphene plasmonic quasicrystal metasurfaces for transformation optics', *Sci. Rep.*, 2014, 4, (5763), pp. 1–8
51. Chen, P.Y., Alu, A.: 'Atomically thin surface cloak using graphene monolayers', *ACS Nano*, 2011, 5, pp. 5855–5863
52. Jablan, M., Buljan, H., Soljagic, M.: 'Plasmonics in graphene at infrared frequencies', *Phys. Rev. B*, 2009, 80, p. 24535 (1–7)
53. Hu, X. & Wang, J. High figure of merit graphene modulator based on long-range hybrid plasmonic slot waveguide. *IEEE J. Quantum Electron.* 53, 7200308 (2017).
54. Lu, Z. & Zhao, W. Nanoscale electro-optic modulator based on graphene-slot waveguides. *J. Opt. Soc. Am. B* 29, 1490–1496 (2012)
55. Liu, R. et al. Experimental demonstration of electro- magnetic tunneling through an epsilon-near-zero metamaterial at microwave frequencies. *Phys. Rev. Lett.* 100, 023903 (2008)
56. Constantine A. Balanis, *Antenna Theory Analysis and Design*, New Jersey: John Wiley & Sons, Inc., Fourth Edition 2016
57. Khaleque, A. et al. Integration of bowtie plasmonic nano-antennas on tapered fiber. *Opt. Express* 25, 8986–8996 (2017).
58. Kushwaha, R. K., & Karuppanan, P. (2020). Enhanced radiation characteristics of graphene-based patch antenna array employing photonic crystals and dielectric grating for THz applications. *Optik*, 200. <https://doi.org/10.1016/j.ijleo.2019.163422>

59. Berry, C., Wang, N., Hashemi, M. et al. Significant performance enhancement in photoconductive terahertz optoelectronics by incorporating plasmonic contact electrodes. *Nat Commun* 4, 1622 (2013). <https://doi.org/10.1038/ncomms2638>
60. Müller, T. et al. A quantum light-emitting diode for the standard telecom window around 1550 nm. *Nat. Commun.* 9, 862 (2018)
61. Khan, M.A.K., Ullah, M.I., Kabir, R. et al. High-Performance Graphene Patch Antenna with Superstrate Cover for Terahertz Band Application. *Plasmonics* 15, 1719–1727 (2020). <https://doi.org/10.1007/s11468-020-01200-z>
62. L. Yousefi and A. C. Foster, “Waveguide-fed optical hybrid plasmonic patch nano-antenna,” *Opt. Express* 20(16), 18326–18335 (2012)
63. M. Saad-Bin-Alam, M. I. Khalil, A. Rahman, and A. M. Chowdhury, “Hybrid plasmonic waveguide fed broadband nanoantenna for nanophotonic applications,” *IEEE Photonics Technol. Lett.* 27(10), 1092–1095 (2015)
64. M. Nikoufard, N. Nourmohamadi, and S. Esmacili, “Hybrid plasmonic nanoantenna with the capability of monolithic integration with laser and photodetector on InP substrate,” *IEEE Trans. Antennas Propag.* 66(1), 3–8 (2018)
65. Dregely, D., Taubert, R., Dorfmueller, J. et al. 3D optical Yagi–Uda nanoantenna array. *Nat Commun* 2, 267 (2011). <https://doi.org/10.1038/ncomms1268>
66. W. T. Sethi, H. Vettikalladi and H. Fathallah, "Dielectric resonator nanoantenna at optical frequencies," 2015 International Conference on Information and Communication Technology Research (ICTRC), 2015, pp. 132-135, doi: 10.1109/ICTRC.2015.7156439
67. Nourmohammadi, A., Nikoufard, M. Ultra-Wideband Photonic Hybrid Plasmonic Horn Nanoantenna with SOI Configuration. *Silicon* 12, 193–198 (2020). <https://doi.org/10.1007/s12633-019-00113-9>
68. W. Sethi, O. de Sagazan, H. Vettikalladi, H. Fathallah and M. Himdi, "Yagi-Uda antenna for 1550 nanometers optical communication systems", *Microwave and Optical Technology Letters*, vol. 60, no. 9, pp. 2236-2242, 2018. Available: 10.1002/mop.31339
69. A. K. Baranwal and N. P. Pathak, "Enhanced Gain triangular patch nanoantenna using Hybrid plasmonic waveguide on SOI technology," 2019 IEEE Indian Conference on Antennas and Propagation (InCAP), 2019, pp. 1-3, doi: 10.1109/InCAP47789.2019.9134564