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Research on Nano Antennas for Telecommunication and Optical Sensing

K. Green[1], R. Vrba[2]

[1,2]*Department of Electrical and Computer Engineering, Mississippi State University, Mississippi State, MS 39762, USA*

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Abstract

Optically resonant nano-antennas represent relatively new and promising functionalities for expanding the uses of optical frequencies in communication and sensing. These nano-scale devices built of metal or dielectric materials, take action through effectively modulating light at the nano-scale, thus avoiding limitations of conventional optical devices, including the diffraction limit. Nano-antennas are pencils of light that have the capacity to focus electromagnetic light energy into highly confined spaces due to their small size; they give precise control of electromagnetic energy which is fundamental for improving the speed, and encoding capacity of optical communication networks. Nano-antennas have higher responsivity to changes in the environment; thus, they can be used in biosensing and environmental sensing with improved capability in detecting small changes in molecular or chemical concentrations. Besides integrating them into photonic circuits may enable the shrinking of the size of optical devices as well as improving the performance of the devices. This paper discuss the application of nano-antennas and studies the design, material and fabrication method with high efficiency, low loss and preferable radiation characteristics for use in different application. Further research in the development of nano-antennas will expand High-speed data transmission, real time sensing, optical system miniaturization that will enhance telecommunication, medical diagnostics, and nanotechnology innovations.

Author's e-mail: Vrbar19s@msstate.edu

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Introduction

Present-day optical sensing development is on the brink of a revolution propelled forward by the beamforming antennas and the nano-antennas. These high technology systems are expanding the limits of sensitivity and gain in optical systems while offering the vast potential of telecoms and much more. To push the performance of optical sensors forward, scientists are exploring the attributes of new and advanced materials such as graphene and effects in the terahertz area(Figure 1).[1]

Here in the introduction, we introduce the basic principles of nano-optics and brief descriptions of the optical beamforming methods to be used in this field. We will also discuss various nano-antenna configurations and issues that enable efficient cooperation between them. This article will provide an insight into signal processing techniques that are seminal for implementation of optical beamforming techniques and future telecommunication applications. Last but not least, we will present new substances which will dictate the further evolution of nano-optics examining the change of such characteristics as refractive index and conductivity.[2]

Fundamentals of Nano-Optics

Nano optics is an area of research that is interconnected with Nanotechnology and the nature of optics generally studying phenomena that occurs at subwavelength scale. This domain has made new developments in controlling and formating light which has improved several fields such as in communication and sensing.

Light-Matter Interactions at Nanoscale

In systems where dimension is limited to nanoscale, incidence of light is completely different from that observed in large systems. The behavior of light gets increasingly modified when it interacts with various media to cause phenomena that are useful in certain applications. These interactions are important for

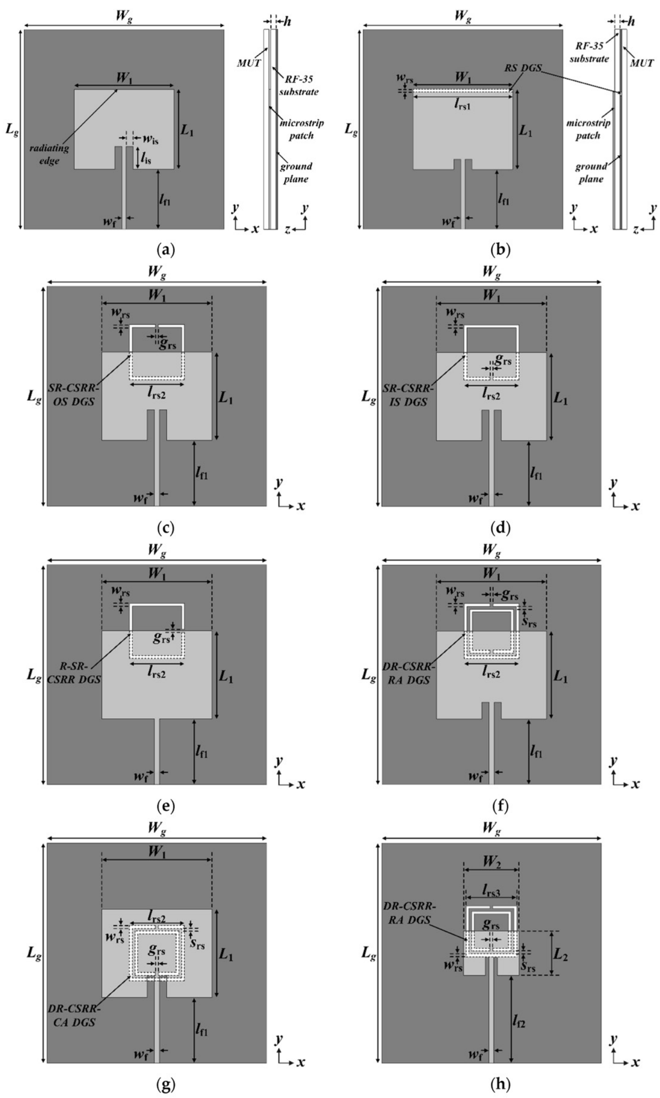

Fig. 1. Nano-antennas

the future growth of different types of advanced optical sensing like beam forming antennas and nano antennas. Another direction of the enhancement of light-matter interactions on the nanoscale is associated with field confinement or field enhancement. A similar confinement is often used to enhance the sensitivity and gain in optical systems; it is even possible to visualize individual molecules. For example, researchers have shown that biomolecules are detectable by Reversible hydrogenation of graphene and binding of streptavidin-biotin with an areal mass sensitivity at the femtograms per square millimeter level.

Near-field and Far-field Optics

It is essential in nano-optics to draw a line between the near-field and the far-field. The near field is the space near a source with distance less than one wavelength and non-radiating properties appear dominant. In contrast the far field is the portion of space where electromagnetic radiation characteristics control. Near field the electric and magnetic fields are separate and one may be much greater than the other. This feature opens the way to construct near-field microscopy methods that are capable of exceeding the actual limiting wavelength and providing sub-diffraction resolution. Rather, the far field is more involved to do with the 'normal' radiation of the electromagnetic field. In this region, electric and magnetic fields reduce as the distance of their sources inversely with square of distance. This behavior is particularly helpful for applications like telecommunication where electricity needs to travel for long distances.

Plasmonics and Metamaterials

Nano-optics subdiscipline called plasmonics deals with the phenomena associated with the coupling of EM fields with free electrons in metals. This interaction results to formation of Surface Plasmons; these are quasi-particles that are associated with collective oscillations of electrons at the Metal Dielectric interface. Nanoparticles can trap light at the sub wavelength scales thereby providing strong enhancement of the local electromagnetic field and various uses such as sensing and imaging. Metamaterials, operative synthetic constructs with properties not present in naturally occurring materials, have assumed a key position in nano-optics. These materials can have negative refractive index and other such extraordinary electromagnetic characteristics which make the concept of unexplored optical applications. Among the up and coming types of metamaterials, plasmonic metamaterials are perhaps the most unique because they incorporate both the advantages of plasonics and metamaterial engineering to manipulate light at the nanoscale. Another interesting implication of plasmonic metamaterials is in the achievement of reconfigurable devices functioning in the terahertz and infrared ranges. Through the use of materials such as the graphene, scientist has developed metasurfaces that are capable of controlling the amplitude, phase and polarization profile of the EM waves. These developments brought into reality subdiffraction lenses, efficient modulators, switches and beamformers enhanced the domain of optical sensing and telecommunication technology.[3]

Beamforming Techniques in Optical Regime

Optical beamforming has been recognized as a versatile tool for boosting functionality of optical sensing and communication systems. Opticians and researchers have come up with unique techniques to control the spatial characteristics of contract light and to guide, structure and focus optical beams, with high accuracy. All of these have enabled application areas in telecommunication, LiDAR systems, applications in medical imaging.

Spatial Light Modulation

Spatial light modulators (SLMs) have become indispensable tools in optical beamforming. These devices can control the intensity, phase, or polarization of light in a spatially varying manner. SLMs based on liquid crystal displays (LCDs) or liquid crystal on silicon (LCOS) technology have gained popularity due to their versatility and programmability. The working principle of SLMs relies on the optical and electrical anisotropy of liquid crystal materials. By applying varying voltages across the liquid crystal cells, the orientation of the molecules can be precisely controlled. This, in turn, modifies the refractive index and optical path length within the cell, allowing for dynamic phase modulation of the incident light. SLMs have found applications in various fields, including holography, quantum optics, and deep learning. Their ability to generate complex wavefronts has made them particularly useful in creating higher-order modes, optical vortices, and Bessel beams. These specialized beam shapes have applications in material processing, optical trapping, and advanced microscopy techniques.

Optical Phased Arrays

Optical phased arrays (OPAs) represent another promising approach to beamforming in the optical domain. Similar to their radio frequency counterparts, OPAs consist of an array of optical emitters whose phases can be individually controlled to achieve beam steering and shaping.

Recent advancements in silicon photonics have enabled the development of compact and scalable OPA devices. These integrated photonic circuits offer several advantages, including low power consumption, small form factor, and the potential for mass production using existing semiconductor fabrication techniques.

One notable example is a 64-element OPA that incorporates electro-optic p-i-n phase shifters and thermo-optic tunable grating radiators. This device demonstrates a field of view of 46.0° × 10.2° with a beamwidth of 0.7° × 0.9° at a wavelength of 1.532 μm. The use of electro-optic phase shifters helps to address the limitations of power-hungry thermo-optic shifters, which have been a concern in earlier designs.

OPAs have shown great promise in LiDAR applications for autonomous vehicles. By combining OPAs with tunable lasers, researchers have demonstrated two-dimensional beam scanning capabilities. This approach eliminates the need for mechanical components, resulting in more reliable and compact solid-state beam scanners.[4-5]

Adaptive Optics

Optical beamforming has been greatly advanced through the use of AO due to real time correction of wavefront distortions. AO which was initially intended for astronomical imaging has other uses in laser fabrication, medical image and free-space optics communication.

In laser fabrication, AO systems allow accurate control of a localized intensity spatial and temporal shape at the focus of the laser. This capability facilitates intricate control of the laser focus which has broad implications in material processing and 3D printing. For example, AO elements may be configured to produce a ‘flat top’ intensity profile that is useful in cutting on the surface of a range of materials.

The combination of AO with lase fabrication gives many advantages for example possibility of adaptive parallelism combined with arrays of foci. The use of computer programs in condition evaluation and adopted recommendation formulation can drastically lower the length of time taken to process outcomes of condition evaluation while enhancing general effectiveness. Furthermore, since the AO elements are adaptively tunable during the fabrication, they can be tailored to shape the beams in accord with the required morphology of the features which are to be incorporated on the device platform.

Further development of these beamforming techniques in the optical regime is also expected to greatly influence the growth of optical sensing and communications. These techniques of SLM, OPA and AO provide means to control the light in a way that was impossible before, paving the way to much more improved optical systems: sensitive, efficient and versatile.[6]

Nano-Antenna Architectures

Optical Nano-antennas hold the promise of representing a revolution in real time optical sensing in the visible, infrared and even further afield. These structures with sizes of order λ/100 or smaller are capable of providing greater direction-, wavelength-, and polarization-sensitivity. The design of nano antennas have moved to multifaceted architecture in order to match different applications and performances.

Plasmonic Dipole Antennas

Plasmonic dipole antennas have attracted considerable interest because of their potential for manipulation of, and focusing of, electromagnetic fields. Metallic particles

Table 1. Antenna Design Parameters

Parameter	Definition	Units	Impact on Performance
Frequency	Operating frequency of the antenna	Hz	Determines size and type
Gain	Measure of directionality	dB	Higher gain means more directionality
Bandwidth	Range of frequencies	Hz	Determines the range of frequencies antenna can operate on
VSWR (Voltage Standing Wave Ratio)	Measure of signal reflection	Ratio (no unit)	Lower value is better for efficiency

can define the near field to deeply subwavelength areas, where in so-called hot spots the electric or magnetic field is particularly enounced. The origin of hot spots is due to localized surface plasmons (LSP) which are quantized oscillation of the free electron gas in the metal interacting with evanescent electromagnetic wave along the metal interface (Table 1) [7]

The plasmonic dipole antennas depicted below were designed to provide radiation efficiency and directivity. It has been shown that by optimizing the size and dielectric properties of the antenna, excellent performance is possible. For example, an electrochemical technique introduced here enables programming the optical characteristics of dipole antennas in parallel, quickly, and in the absence of significant energy consumption. This method has prospects of improving the work of nano-antennas flexibility and adaptability in some applications.

Yagi-Uda Nanoantennas

A principle of operation well acquainted in the RF domain, the Yagi-Uda antenna, has been successfully scaled to the nano domain. Yagi-Uda nanoantennas are optical antennas in which the feeding element is the active component and is accompanied by a resonant reflector and one or several directors which are equally spaced from the feed element. The outward performance of these elements depends on these elements' dimensions to provide constructive interference in the forward direction and destructive interference in the opposite direction. In the optical range, thin-wire formulas are no longer accurate due to the skin depth which is on the order of the antenna dimensions of Yagi-Uda nanoantennas. This means that some fundamental tenets of RF antenna design have to be revisited, for instance, the actual length of the feeding element must be determined using λ_{eff}. The cross-sectional dimensions and spacing between elements also considerably affect the reduction of absorption losses in metals. Another substantial benefit of the optical Yagi-Uda nanoantennas is their capability to manage the radiation of isolated quantum nanoemitters as quantum dots and colour centres in nanodiamons. When the emitter is positioned in near-field proximity to the feed, near-field coupling can produce extremely directional radiation. This kind of feature makes Yagi Uda nano antennas most suitable for quantum cryptographic, communication and IT based computations.

Metasurface Antennas

Meta-surface antennas could be considered a state-of-art nano antenna geometries which provide enhanced capability for control of electromagnetic waves. Such additional sub-wavelength artificial surfaces can control all aspects of the electromagnetic waves' allowance including and not limited to amplitude, phase, frequency, polarization and momentum. Innovations recently unveiled enable the use of a microwave UMA that can dynamically, simultaneously, independently, and accurately control these properties in real-time through software programming. The UMA is an assembly of a 2D array of anisotropic meta-atoms located on a subwavelength scale above a waveguide layer. These are formed by pairs of $\pm 45^\circ$ inclined, elliptical slot openings with a large length to width ratio. This design makes it possible to derive arbitrary polarization by defining the amplitude ratio and phase shift of the extracted constituent. Another advantage of metasurface antennas is in information control because these structures are able to create time-variable wave characteristics. This capability offers a completely new communication paradigm at the physical level with benefits like reduced complexity, compactness, lesser size, and,inexpensive and lower power consumption than those of conventional systems.

Coupling Mechanisms in Nano-Antenna Arrays

The behaviour of the individual elements of the nano-antenna arrays is highly dependent on the mutual interactions. These coupling mechanisms have been found to greatly influence the characteristics and performance of the array system. Knowledge of these interactions is critical in the development of an efficient nano-antenna array for application in optical sensing and telecommunications.

Near-field Coupling

Near-field coupling is the situation where the Nano-antennas are placed in close region satuating each other, in a distance of less than half the wavelength of the incident light. This type of coupling has a desired influence on the optical behavior of the array to a large extent. When the inter-particle distance decreases further, the major dipole mode shifts to lower energy or red shift due to the large build up of induced charges at the gap and shaking between capacitive coupled plasma oscillations. For gold nanorod dimers, there is strong evidence of the near-field coupling response where it has been established that they can show bonding and antibonding plasmon coupling if the position of the two nanorods is side by side or end to end respectively. This arrangement leads to the activation of dark mode and a symmetry breaking necessary in improving the sensitivity of the device in sensing applications.

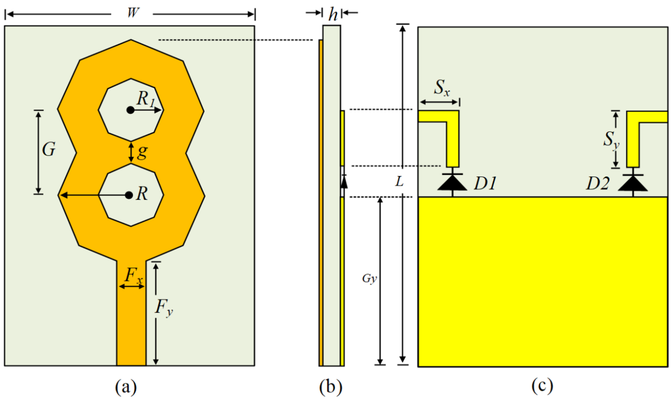

Fig. 2. Coupling Mechanisms in Nano-Antenna Arrays

The intensity of near-field coupling is determined by geometrical parameters of coupled nano-antennas: size, shape and orientation of the nano-antennas as well as the refractive index of the surrounding media. Thus, it is possible to model an array with specified parameters of coupled waveguides and, consequently, to obtain the desired optical characteristics and a higher overall efficiency of the array.

Far-field Interference

Periodic configurations of nano-antennas are characterized by the presence of far-field interference. This type of coupling occurs between the LSPRs of individual nano-antennas and the diffraction modes including the Rayleigh Anomaly of the formed array. These modes of operation can hybridize to create SLRs that possess sharp lineshapes and large quality factors. SLRs are particularly suited for biological and chemical detection in view of the application's potential of supporting high Q factors. They also give us special chances to investigate lasing in the dark and bright modes of plasmonic lattices. The system in far-field coupling may have coherent diffraction coupling leading to a special type of SLRs, where the Rayleigh anomaly wavelength of the array becomes comparable to the collective resonances of the array elements.

Collective Modes

Such phenomena are collective effects, which stem from the field that multiple nano-antennas create influencing the formation of new optical characteristics that do not belong to the array constituents. Th ese modes can be classified into two main categories: edge modes and cavity modes. Edge plasmon modes are localized at the edges of nanostructures, and can be of various multipolar nature. On the other hand, cavity or breathing modes lie more or less at the center of the nanostructures. When these modes are coupled in adjacent nano-antennas, it is possible to obtain the plasmonic supercells with different optical characteristics. When an array of flat metallic nanoantennas (FMNTs) are periodic along one direction, the coupling between elements within that direction may give rise to polarization-dependent coupled resonances. This leads to the creation of two different types of plasmonic supercells: bonding supercells and cavity supercells. Bonding supercells have been defined by optical fields or hot spots in between the FMNT gaps, and on the other hand, cavity supercells have regions of deficient fields between the FMNTs. With respect to the enhancement of the electromagnetic energy density inside the cavities, the coupling of collective modes in nano-antenna arrays can be seen to be sizeable. Published experiments show that the density of the electromagnetic energy can be increased between 104 times while taken per each element with low quality factors. This property makes nano-antenna arrays most suitable for high sensitivity and gain applications of terahertz sensing and communication.

Signal Processing for Optical Beamforming

Optical beamforming is significantly related to signal processing in order to control and process light for various uses such as communication and sensing. Since the increase in the demand of high-speed devices and circuits with minimum energy consumption, the increase in the performance of optical beamforming system has been studied by researchers. This section aims at describing the digital signal processing, analog processing and blended methods applied in the optical beamforming.Chapter 1: Applied Digital Signal Processing Techniquese in optical beamforming, enabling the manipulation and control of light for various applications, including telecommunications and sensing. As the demand for high-speed and energy-efficient devices grows, researchers have developed innovative techniques to enhance the performance of optical beamforming systems. This section explores the digital signal processing techniques, analog processing methods, and hybrid approaches used in optical beamforming.

Digital Signal Processing Techniques

Optical beamforming has recently become a key element in modern communication systems due to its application of digital signal processing (DSP) that allows for accurate control of the direction and form of optical beams. In Digital Beamforming the modulated signals are launched to the antenna array and the phases and amplitudes of the signals required for the required beam pattern are summed up. This approach creates the ability to form several beams from the same base in different directions and/or time, which opens up space division multiplexing and thus system capacity (Table 2).

Another major benefit that must be said about the digital beamforming is that it is highly adaptive to the changing state of the conditions and demands. Through the precoding techniques, the system can select a desirable beam pattern towards the targets or users. The precoding matrix that defines the amplitudes and phase differences for the signals to be transmitted to each of the antenna elements can therefore be calculated real time via software or a system controller such as an FPGA. Nevertheless, digital beamforming can be complex and burdensome with frequently requiring extensive computational processing, especially in a system with numerous numbers of antennas or moving towards the high-frequency band. In order to overcome this challenge, researchers have fashioned the optimal algorithms and hardware structure which helps in doing a lot of calculations for beamforming in real time.

Analog Processing Methods

Analog processing methods are an attractive substitute for optical beamforming, especially for systems that operate at high frequencies or do not have complex specifications. In the case of analog beamforming the phase and amplitude changes are done in the optical signals via components such as phase shifters and attenuators. The first benefit of using analog processing is that it is easier to process the wideband signals than to have the techniques used in digital signal processing. This makes it particularly suitable for use in applications based in the terahertz region of operation in which the bandwidth to the center frequency ratio is quite large. It can also be more power efficient for a number of applications because there is no requirement for fast ADCs and digital beamforming electronics. However, the analog beamforming could be physically complex to implement and perhaps not easily scalable for huge antenna array especially when fine form control of multiple beams is needed. Another challenge, which may be more prominent and implied by analog beamforming, is the requirement of system level synchronization within multiple transceiver elements.

Hybrid Approaches

To overcome the limitations if a purely digital or analog scheme of beamforming, researchers have incorporated ideas from both of these methodologies in the so-called hybrid beamforming strategies. These methods incorporate DSP with the practically RF based beam forming using sub-arrays, which provide good balance in terms of configurability and capability along with the requisite level of sophistication. In a hybrid beamforming system, the main system controller controls multiple ADC/DAC and power amplifier using a high speed digital interface plus an embedded clock. This approach makes it possible to create the multiple beams and, at the same time, maintain the degrees of freedom for the spatial multiplexing together with adaptability to the prevailing circumstances. The use of hybrid beamforming is especially noteworthy for the development of millimeter-wave and terahertz communications, as high frequencies and large bandwidths complicate the use of only digital

Table 2. Antenna Performance for Different Frequencies

Frequency Band	Wavelength	Suitable Antenna Type	Common Applications
Low Frequency (LF)	30 - 300 kHz	Loop Antenna	Submarine communication
High Frequency (HF)	3 - 30 MHz	Dipole, Yagi-Uda	Amateur radio, Shortwave
Very High Frequency (VHF)	30 - 300 MHz	Yagi-Uda, Log Periodic	TV broadcasting, FM radio
Ultra High Frequency (UHF)	300 MHz - 3 GHz	Microstrip, Patch	Wi-Fi, Cellular networks
Super High Frequency (SHF)	3 GHz - 30 GHz	Parabolic, Horn	Radar, Satellite communication

or only analog solutions. The advantage of combining both method is that, hybrid systems are more efficient in achieving high gain and better sensitivity than using the two techniques separately while having the flexibility to cover any changes in channel conditions and users wishes. The specific functional materials and designs for optical beamforming are still under investigation, as new technology is developed for more performance improvement. For instance, the integration of advanced graphics such as graphene and others, possessing different refractive index and conductivity characteristics than the traditional provisioning materials, may lead to actual creation of enhanced and further compact beamforming systems especially for the market of terahertz.

Applications in Telecommunications

The advanced technology of new optical sensing plays a role in beamforming antennas and nano-antennas to take a turn in telecommunications. These have made it easier to provide advanced technologies in more improved and high-speed communication systems possible, with solutions for the fundamental issues in telecommunication systems cutting across several telecommunication applications.

Free-Space Optical Communications

Free-space optical (FSO) communication has been developed as a promising technology of the wireless data transmission through the light signal propagated in free space. Several benefits can be derived from using this approach over the conventional RF systems such as high bandwidth capability, enhanced security, and low level of EMC. A sort of antennas known as beamforming is used in the regulation of gain and sensitivity in FSO systems. This is true because with FSO communication, there are increasing chances of receiving high data rates such as fiber optic connections. Current widely spread FSO networks have data bandwidths of 100 Mbps- 10 Gbps, however there are several high end prototypes exercising data bandwidth of 160 Gbps. For such applications as inter-satellite communication and terrestrial communication in metropolitan cities, FSO possesses this high speed feature that makes it suitable for use. However, FSO systems are subjected to challenge by some atmospheric factors some of which includes fog, rain and dust which interfere with the quality and reliability of signals being transmitted. To these concerns, researchers are considering employing advanced material such as graphene in beamforming antennas. Based on the features of graphene such as high conductivity and a refractive index that can be easily tuned, it show a potential of enhancing the performance of the FSO systems in the terahertz region.

Optical Wireless Networks

Optical wireless networks are and can be used as an opportunity to increase information transmission capacity of some communication networks. These networks rely on Broadband Wireless Communication to convey signals via several channels within diverse frequency bands. Thus beam forming antennas and nano-antennas can be implemented in optical wireless network for achieving high directivity and gain in a wide range of frequencies. Notable application of this has been in the development of broadcast optical wireless networks. Such networks often include a transmitter, a WDM wireless router, and multiple receivers, as a rule. The WDM router allows the broadband signal to be divided into several channels with predetermined wavelengths that will direct the signals to the corresponding receivers through horn nanoantennas. By exhibiting non-resonant behavior, horn nanoantennas can be used for broadband nanopulsed optical wireless communications. This capability expands the opportunities to integrate much more complex network topologies in the chip scale photonic nanocircuits and improve their functionality.

Inter-chip Optical Links

As the need to transmit data at much higher rates and with increased efficiency to and from electronic devices, inter-chip optical links are proving as promising technology to be pursued. These links are designed to replace the conventional electrical interconnects with optical connections promising higher bandwidth and lower power consumption. Special focus is made on the use of beam forming antennas and nano antennas for wireless optical communication between chips. Small-scale wireless ‘near-infrared links’ in excess of 10 Gbps have also been shown by researchers to be possible by linking the optical signal to electrical current represented by rectifying antennas all at nanoscale. By having each chip independently manage its own inter-chip communication needs, several benefits are provided including the possible existence of actual high-speed informative exchange capacities surpassing 1012 bits per second. The response of these systems is fast since the plasmonic properties are defined by the polarizability of the metal not the lifetimes of the carriers in semiconductors.

Emerging Materials for Nano-Optics

The nanooptics research area is a rapidly evolving field, which has not only been expanded by the introduction of novel materials of higher light-matter interaction. These emerging materials are expanding applications for optical sensing and telecom, and have potential for applications in beamforming antennas and nano-antennas with high gain and sensitivity.

2D Materials for Plasmonics

Two-dimensional (2D) materials have been reported as potential materials for plasmonic use in nano-optical systems. DUE to their electronic structures and physical properties these systems offer unique potentials for exploration of new scale small optoelectronic devices. Of all these 2DMs, graphene has attracted the most interests because of its high electrical conductivity as well as its ability to have its refractive index tailored within the terahertz regime. Plasmonic surroundings are another asset of 2D materials due to which the light matter interface can be significantly improved. This coupling has increased the photoluminescence quantum yield, strong plasmon-exciton coupling and nonlinear optical processes in plasmonic nanoparticles. This also applies to the out-of-plane van der Waals interaction which makes it easier to incorporate 2D materials into different nanophotonic structures for devices.

Quantum Dots

QDs are now an undeniable part of any researcher's nano-optics toolbox. These semiconductor particles at the nanoscale level show optoelectronic properties eventually, owing to quantum size effects. Among these nanoengineered materials, colloidal quantum dots have demonstrated remarkable potential for application in biological tagging, LEDs and solar energy conversion. New findings in QD synthesis have directed the fabrication of core/shell structures, the most common being, CdSe/ZnS that exhibits better photostability and luminous efficiency. These improved characteristics make QDs ideal for infrared applications in which they are superior to ordinary organic dyes. Opportunities to control am and em spectra of QDs enable the design of new efficient beamforming antennas with selective optical properties.

Conclusion

Next, substances with PCMs have become ideal for nonvolatile resonance tuning of the nanophotonic components. These materials can exhibit reversible, thermo-induced changes between amorphous and crystalline phases, leading to drastic changes in their optical and electric characteristics. This rather peculiar feature makes PCMs suitable for forming reconfigurable nano-antennas and bifunctional beamforming devices. The incorporation of PCMs with plasmonic structures has boosted the advance of reconfigurable metasurfaces and optical switchgear as well as elevated sensitivity and gain. Recent efforts include the phase-change property of GeSbTe for on-chip, dynamic, tunability of optical elements in the THz and IR ranges.

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