Chapter 8

Graphene-Based Acousto-Optic Sensors with Vibrating Resonance Energy Transfer and Applications

Burhan Gulbahar and Gorkem Memisoglu

Additional information is available at the end of the chapter

http://dx.doi.org/10.5772/intechopen.73618

Abstract

Graphene as a two-dimensional planar material has numerous advantages for realizing high-performance nano-electromechanical systems (NEMS) such as nanoscale sensors including strain sensors, optical modulators or energy harvesters. Large Young's modulus (1 TPa for single layer graphene), ultra-low weight, low residual stress and large breaking strength properties are important properties as two-dimensional (2D) ultrathin resonators. Graphene resonators are recently utilized for low complexity design of nanoscale acousto-optic sensors based on a novel theoretical model describing vibrating Förster resonance energy transfer (VFRET) mechanism. Proposed system combines the advantages of graphene with quantum dots (QDs) as donor and acceptor pairs with broad absorption spectrum, large cross-sections, tunable emission spectra, size-dependent emission wavelength, high photochemical stability and improved quantum yield. Device structure supporting wide-band resonance frequencies including acoustic and ultrasound ranges promises high-performance applications for challenging environments. Remote sensors and acousto-optic communication channels are formed for in-body applications, wireless body area sensor networks (WBASNs), space and interplanetary systems, microfluidics and visible light communication (VLC)-based architectures.

Keywords: nano acousto-optic sensor, graphene resonator, nanoscale acousto-optic transduction, vibrating Förster resonance energy transfer, energy harvesting, interplanetary communications, in-body sensor network, microfluidics, visible light communications

1. Introduction

Graphene has important advantages in significantly many application areas of physical, chemical and biological sciences with advanced engineering system designs including sensors, modulators and two-dimensional (2D) ultrathin resonators. Mechanical designs utilizing graphene achieve high-performance nano-electromechanical systems (NEMS) with large Young's modulus (1 TPa for single layer graphene), ultra-low weight, low residual stress and large breaking strength, i.e., graphene strain allowing 25% without breaking [1]. Unique optical, electrical, physical and mechanical properties of graphene allow the designed resonators to be utilized in challenging applications, e.g., strain sensor, mass sensor, nanogenerators, transducers, photodetectors and novel NEMS devices [1–8].

Nanoscale photonic solutions with a novel design for sensing, energy harvesting or communication purposes are recently presented in [3–5, 8] with significant performances and rich set of applications. They utilize unique and unexploited features of graphene and quantum dots (QDs) combined with a special mechanical design. QDs are future promising as donor-acceptor couples in next generation nanoscale devices [3–5, 8, 9]. More specifically, passive acousto-optic nanoscale optical modulator design is presented by exploiting high performance mechanical properties of graphene resonators and radiating photon emission from QDs with a novel method denoted by vibrating Förster Resonance Energy Transfer (VFRET) [4]. It promises high performance applications in biomedical, space and microfluidic monitoring and tracking areas while utilizing energy harvesting, low complexity and all-in-one acousto-optic transducer mechanical design.

VFRET mechanism uniquely exploits important properties of graphene resonators having wideband spectrum covering acoustic and ultrasound frequencies combined with special features of QDs, and FRET which is a nanoscale energy transfer process between two molecules denoted as donors and acceptors [4]. FRET utilized in a rich set of biological, physical and chemical applications such as monitoring cellular activities has also been utilized for nanoscale communication channels [10–12]. Semiconductor nanocrystal QDs form a unique cooperation with graphene resonators by utilizing high performance properties such as sharp and broad absorption spectrum, large absorption cross-sections, tunable emission spectra and wavelength, photochemical stability and photoluminescence quantum yield [13, 14]. In [4], a modulator is designed to be utilized in challenging applications for communications, sensing and energy harvesting with a scalable range including both nanoscale and macroscale dimensions. Ambient light sources with low power levels are utilized instead of laser sources in a nanoscale hybrid acousto-optic platform while periodically modulating nanoscale distance between donors attached on vibrating graphene and acceptors fixed on a support. Therefore, a design combining flexibility without requiring special laser set-ups, energy efficiency with low power ambient sources and wideband resonance frequency including ultrasound levels is presented as a future promising tool. In addition, it is emphasized that graphene vibration can also be generated by thermo-acoustic or opto-acoustic methods by proposing the tool beneficial in significantly challenging environments.

VFRET system design promises important application areas as discussed in detail in Section 5 by combining unique properties of QDs and graphene including its biocompatibility. Various application areas are listed as follows presenting biomedical, space, microfluidics and communication purposes:

1. **Biomedical applications:**

    a. In-body: hybrid acousto-optic noninvasive communication channels inside body by utilizing external acoustic excitations.

    b. Wireless body area sensor networks (WBASNs): wearable sensors such as heart rate monitoring or any sensor transmitting data with optical sequences.

2. **Space applications:**

    a. Interplanetary remote sensing: sensing atmospheric events remotely.

    b. Optical wireless communications: realizing optical channels between devices in space environment.

3. **Microfluidics:** cell and particle monitoring and tracking.

4. **Visible light communications (VLC):** generating visible light sequences with advanced geometrical design to produce modulated data sequences.

In this Chapter, VFRET mechanism and nanoscale acousto-optic sensor design are briefly introduced in Sections 2 and 3, respectively, as fundamental novel tools described in [4]. Then, Section 4 discusses applications in biomedical sensing, interplanetary and space, microfluidics and communication networks. Finally, Section 5 concludes the Chapter with a brief summary of VFRET-based sensor design and its applications.

2. Vibrating FRET mechanism

An illustration describing the basics of VFRET mechanism is given in **Figure 1**. Vibrating multi-layer graphene membrane has height h, radius a, tunable donor-acceptor (D-A) distance of d_{AD} and resonance amplitude d_0. Three phases of VFRET are denoted by phase-a, phase-b and phase-c. Phase-a corresponds to the position at rest. FRET or VFRET occurs in phase-b at the shortest distance between D-A pairs and phase-c has the largest distance

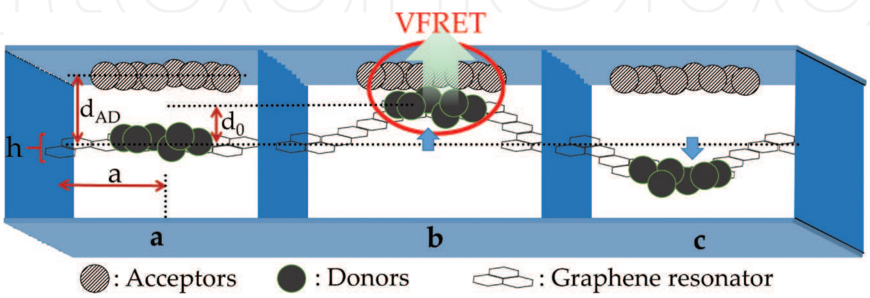

Figure 1. Nanoscale acousto-optic transduction mechanism with VFRET mechanism where mechanical vibration is converted to optical emission (adapted from [4]) with the phases denoted by a, b and c showing the relative positions of acceptors and donors in a single resonance period.

between the pairs without any FRET emission. QD donors are attached on graphene membrane firmly, while acceptor molecules are either the QDs or fluorescent dyes, and attached on top of the modulator frame.

Radiated light is controlled by modulating acoustic pressure on graphene resonator while donors are continuously excited by visible light sources. The number of photons emitted is modeled as follows [4]:

$$N_{FRET} = \Delta_t I_D D_B \sigma_D \Phi_A E N_D / \left(h_p f_D^a\right) \tag{1}$$

where Δt is the photon counting time interval which is much larger than the total time $t_p = t_D + t_{FRET} + t_A$ for acceptor emissions summing the donor excitation time denoted by t_D, FRET time t_{FRET} and acceptor emission time t_A, I_D and D_B are the light intensity in (W/m²/nm) and bandwidth in (nm), respectively, for donor excitation, $\sigma_D = D_{ext} \times 3.825 \times 10^{-23}$ denotes absorption cross section of donor excitation in (m^2), D_{ext} is donor extinction coefficient in (M^{-1} cm^{-1}), Φ_A is the quantum yield of acceptors, E is FRET efficiency, N_D is the number of donor molecules, $f_D^a = c/\lambda_D^a$ is donor excitation frequency, $c = 3 \times 10^8$ (m/s), λ_D^a is the donor excitation wavelength, and $h_p = 6.62 \times 10^{-34}$ (J × s) is Planck's constant. FRET efficiency E is defined as follows [4]:

$$E = \frac{k_A R_0^6}{d^6 + k_A R_0^6} \tag{2}$$

where k_A denotes the number of acceptors corresponding to each donor, d is the donor-acceptor distance, and R_0 is Förster distance.

In the next section, proposed model is utilized to design an acousto-optic sensor composed of mainly vibrating multi-layer graphene membrane and D-A molecules.

3. Nanoscale acousto-optic sensor design

The proposed design is improved by including lenses, supports and special enclosure design to be utilized in challenging environments as shown in **Figure 2** as described in detail in [4]. Donors absorbing incoming light energy transfer the energy to acceptors while received and emitted light are filtered by a combination of optical lens and filter to prevent unintended acceptor emission and to intensify incoming and emitted light.

Graphene layer acoustically vibrates with minor change on the resonance frequency due to the weight of donor molecules. The distance between D-A pairs is tunable with respect to the desired vibration amplitude. An example is shown in **Figure 3** where multi-color emission capability is realized by including an array of resonators with different color emissions tuned to different sound pressure levels (SPLs). The set of D-A pairs in [4] is extended in **Table 1** to include multiple colors, and a diversity of D-A pair selections with different diameters and types, i.e., dyes, QDs and proteins [13, 14]. Excitation wavelengths of donors and acceptors,

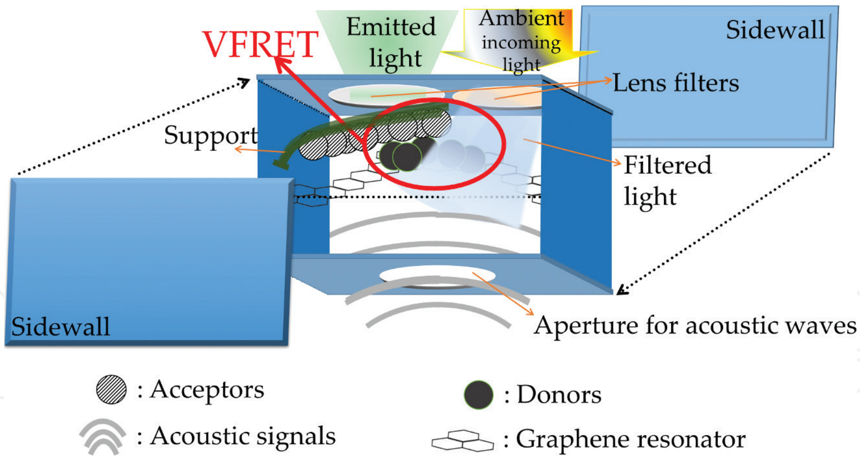

Figure 2. Physical structure of the acousto-optic transducer where QD donors on resonating graphene membrane transfer energy to QD acceptors on the support with VRET mechanism [4]. Acceptors have filtering interfaces for incoming and emitted light sources while resonators are vibrated by acoustic waves entering through aperture. Sidewalls and special geometrical design protect the device and provides durability (adapted from [4]).

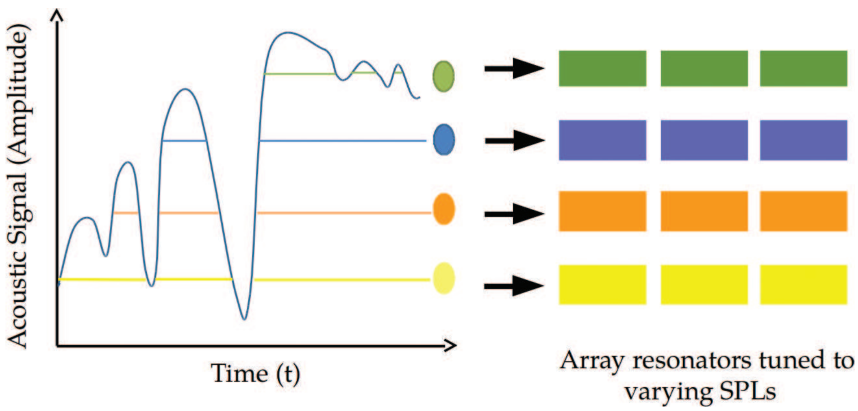

Figure 3. Resonators tuned to varying sound pressure level (SPLs) with different colors at the corresponding SPLs and arrays of resonators enhancing emission intensity.

Ref #	Donor and diameter	λ_D^a	λ_D^{PL}	Acceptor and diameter	λ_A^a	λ_A^{PL}	R_0	Φ_A
[13]	CdSe/ZnS (2.5 nm)	475	500	Dye (fluorescein27)	505	548 (green)	3.4	0.6
[14]	CdSe/ZnS (2.9 nm)	540	555	CdSe/ZnS (3.7 nm)	560	580 (yellow)	6.6	0.6
[14]	Cyan fluorescent protein	430	495	Yellow fluorescent protein	500	525 (green)	4.5	0.4
[14]	CdSe/ZnS (3.7 nm)	555	570	Fluorescent protein mCherry	575	615 (red)	5.8	0.6
[14]	CdSe/ZnS (3.3 nm)	510	550	CdSe/ZnS (3.3 nm)	555	590 (yellow)	6.1	0.6

CdSe/ZnS: cadmium selenide/zinc sulfide.

Table 1. Extended set of D-A pairs to utilize in acousto-optic sensor and modulator.

i.e., λ_D^a and λ_A^a, respectively, and emission wavelengths denoted by λ_D^{PL} and λ_A^{PL}, respectively, are tuned with changing diameters and types of molecules.

In addition to QDs, dyes and proteins are candidates to be utilized in various application environments depending with respect to the requirements. In the next section, applications of the proposed sensor and modulator devices are discussed.

4. Applications

The application areas of the proposed VFRET device include a diverse set of domains with various tasks of the device such as an acousto-optic sensor, modulator and hybrid communication transmitter. In-body hybrid sensors, WBASN applications with wearable sensors and transceivers, microfluidics, space, on-chip communication transceivers and visible light communications (VLC)-based applications are the most promising ones as discussed in the following sections.

Bio-compatibility of graphene and QDs gives opportunity for further improving the proposed design suitable for in-body applications [2, 15, 16]. More promising future applications include biomedical ultra-low power communication networks, acoustic sensors and transducers, and nanophotonics. In addition, array structures utilizing multiple resonators in horizontal and vertical dimensions improve light emission power.

VFRET-based nanoscale sensor/modulator architecture allows high performance future applications by exploiting important features of the special design with graphene and QDs. The proposed device brings unique advantages by exploiting the following features:

- Planar architecture to be attached on varying objects
- Lightweight design
- Broadband spectrum capability supporting ultrasound and acoustic waves
- Energy efficient design operating with low level of light sources such as ambient light levels for day time and LED sources for night time operation
- Passive and energy harvesting design by combining vibration and external light sources
- Hybrid acousto-optic architecture allowing utilizing ultrasound and acoustic signals for challenging environments such as creating optical communication links inside body by using external ultrasound vibrations
- Tuning to different frequencies, SPLs, light levels and applications by varying device geometry, graphene resonator and the number of QD molecules
- Flexible system design without requiring complicated laser set-ups having strict orientations
- Adaptability to different application areas including in-body communications, wireless body area networks (WBANs), nanoscale and microscale communication networks, microfluidic monitoring and tracking applications, space and aerial applications, and VLC.

http://dx.doi.org/10.5772/intechopen.73618

Next, various application areas including biomedical sensing, interplanetary remote sensing and space applications, microfluidics and VLC are discussed in detail.

4.1. Biomedical sensing and communications applications

Biomedical sensing is an emerging and future promising topic with various applications including wearable sensors, wireless body area networks (WBAN), and in-body sensing and communications applications [16]. Proposed lightweight and energy efficient device structure is a low complexity and all-in-one alternative to the existing radio frequency (RF)-based WBAN sensor solutions [17]. Potential applications include heart tracking, mobility or any movement related monitoring of body parts. In **Figure 4**, an architecture is provided where acoustic vibrations of heart within specific frequency bands reaching hundreds of Hz are converted to optical emissions with tuned device geometry as indicator of heart rate signaling [18]. It provides a passive heart rate monitoring device without requiring battery and, separate modulator and coding blocks with complicated architectures.

In disaster scenarios, heart rate monitoring device provides a method to track and to monitor the health condition of the people remotely. In addition, multiple people including highly crowded groups can be tracked by monitoring emitted periodic sequences. A simple and remote personal monitoring device is proposed.

Besides that, it allows to realize communication channels inside body, e.g., for hybrid communication links for intra-bone communication architectures as discussed in [19] and as shown in **Figure 5**. Remote signal transmission and communication with in-body region by using transceivers outside the body are highly difficult with RF and optical signals. On the other hand, ultrasound signals easily penetrate through body. A hybrid communication channel is formed by modulating the device inside the body, e.g., bones, with an external ultrasound excitation while emitting optical signals inside the bone region for optical communication. Therefore, optical communication channels anywhere inside the body are easily formed by exciting externally with ultrasound waves.

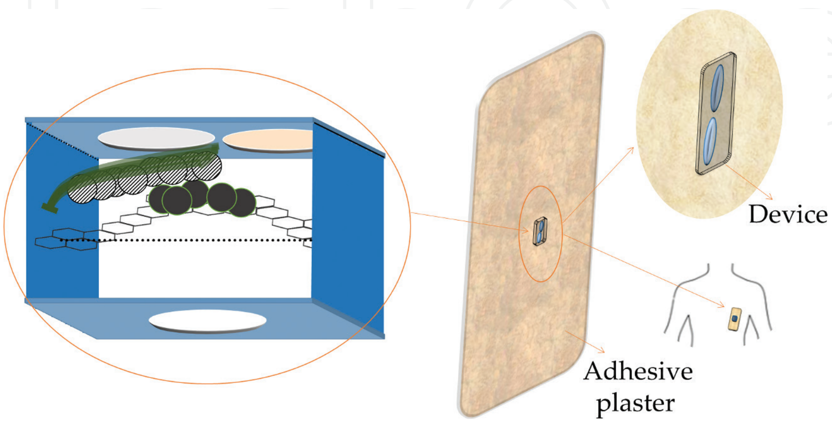

Figure 4. Biomedical sensing for heart rate monitoring where acousto-optic transducer device is attached on the surface of the heart with an adhesive plaster.

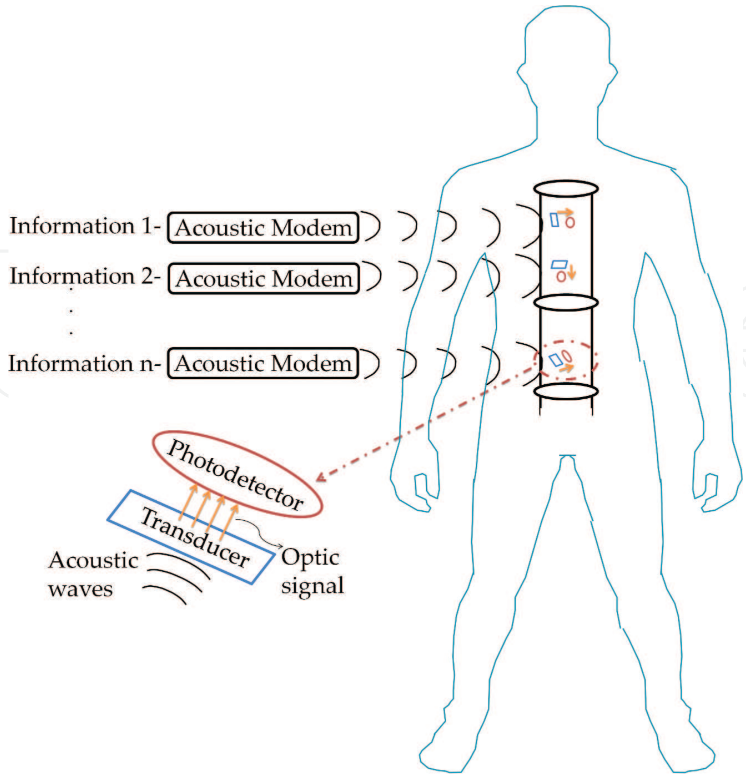

Figure 5. Hybrid in-body sensing and communication scenario for realizing optical communication links inside the body with external acoustic excitation. Photodetectors detect acousto-optic signals inside the bones as a challenging medium to realize communication networks.

In-body applications are realized by exploiting acousto-optic transduction properties, energy harvesting, low power operation and unique features of graphene and QDs. Hybrid communication links are formed such that graphene resonator is vibrated remotely without requiring contact by using ultrasound waves for creating optical in-body networks. Noninvasive design promises to improve opto-genetics with capability to operate inside different parts of the body [20]. In-body system design requires low power LEDs to be available with the proposed device. This is feasible compared with high power laser operations requiring strict orientations and complicated set-ups. Scalability of the geometrical design, planar structure, flexible and simple system design, and all-mechanical structure make VFRET design with graphene resonators more promising for challenging optical in-body nanonetworks.

Information is externally generated and transmitted to photodetectors inside the body by using external acoustic modulation and hybrid acousto-optic transduction in the VFRET device as a solution for significant challenges of the optical or RF signals to penetrate inside the body [16].

4.2. Interplanetary remote sensing and space applications

Long range acoustical sensors are utilized for passive sensing of vibrations, flutter, atmospheric turbulence, and terrestrial and planetary sounds remotely [21]. Utilization of reflective surfaces with the light shining on the diaphragm limits the practicality of these devices. On the other hand, proposed acousto-optical system architecture allows nanoscale architectures, flexible design with a controlled light source without any reflection-based positioning requirements and multi-color light modulation. Atmospheric events and space-based environmental sensing applications of vibrations are easily tracked with optical signal detection where the light energy is harvested from high power and line-of-sight radiation of the sun as shown in **Figure 6**. Hard-to-reach areas where vibratory events occur are monitored with a sensor network composed of energy harvesting transducers with significantly high lifetimes, durability and low complexity design allowing long duration space travel.

On the other hand, energy harvesting nature and optical emission capability are utilized for creating optical wireless communications channels in space. Simple device mechanism and array forming capability provide a unique opportunity to utilize in challenging environments in space.

4.3. Microfluidic applications

Multi particle tracking (MPT) or single particle tracking (SPT) with labeling by observing fluorescent molecule emission are common tools for monitoring cellular processes for in-vivo nano-biological and in-vitro microfluidic systems [3, 5]. Special fluorescing tags attached on molecules are tracked and digital image processing tools allow nanometer (nm) resolution in positioning. Image processing methods and algorithms are developed in significantly many studies for particle and cell tracking in microscopic platforms [22, 23]. However, there are important challenges for collection capability and analyzing high complexity imaging data. Tags do not have signaling capability to support a signaling-based tracking compared with traditional imaging-based tracking systems like fluorescence lifetime imaging for cell tracking.

Recently, a novel nanoscale acousto-optic radar and particle tracking system design using chirp spread spectrum (CSS) sequences with special geometrical design of acousto-optic transducers [5]. The design denoted with the name *CSSTag* promises signaling-based tagging in microfluidic environments by generating unique tags as shown in **Figure 7**. CSSTag system utilizes spread

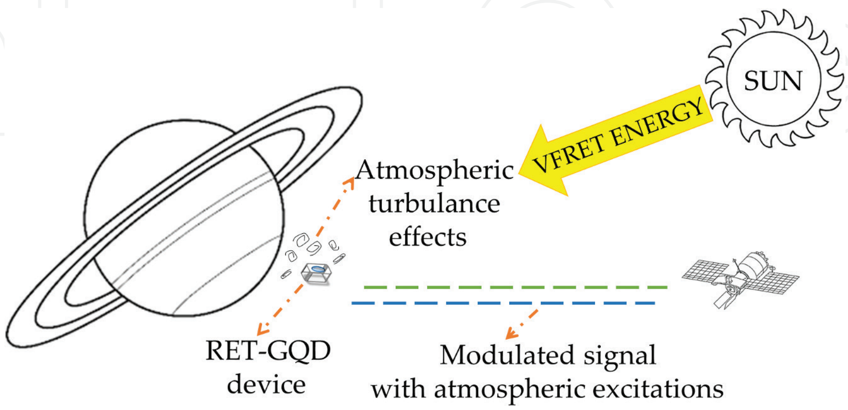

Figure 6. Space application for interplanetary remote sensing where energy is harvested from sun to track acoustic vibrations of atmospheric effects in space or planetary environments.

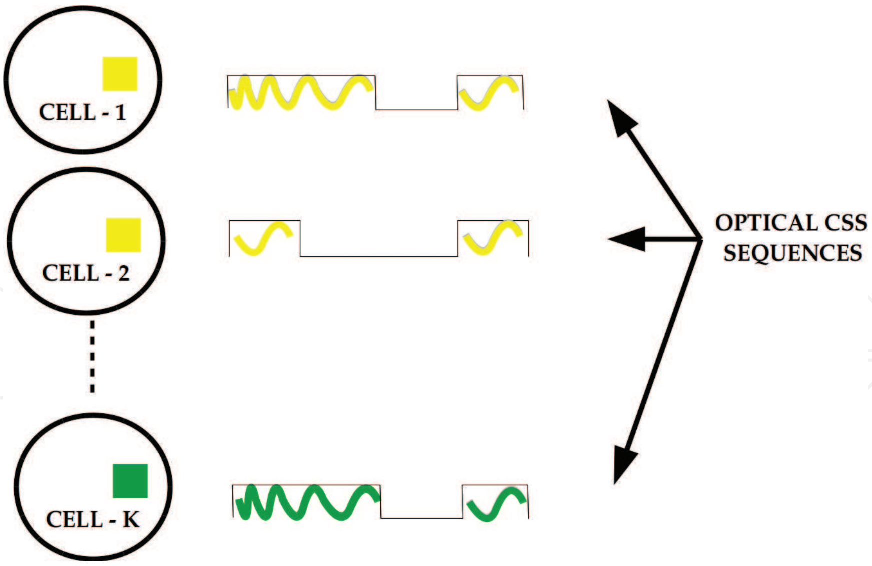

Figure 7. Multiple optical sequence generation for tagging different cells where the first two cells are tagged with the same color but different sequences while K^{th} cell is tagged with same sequence with the first cell but with different color.

spectrum modulation, time difference of arrival (TDOA)-based positioning and cell specific signaling sequences by exploiting the theoretical design providing nanoscale acousto-optic transduction with VRET and graphene resonators. Ultrasound carrier vibrated graphene resonators with specially placed multi-layer geometrical design to produce different optical emission sequences which are detected by a set of photodetector arrays with color filters.

4.4. Visible light communications

The capability to generate modulated optical signals in visible frequency band allows to realize nanoscale VLC transmitter at the resonance frequency of the membrane utilizing various modulation structures [24]. Multi-color emission capability and spatial diversity support generation of more advanced modulation methods such as color shift keying (CSK) as one of the important standard methods in VLC. The proposed device is embedded either into on-chip platforms for intra-chip hybrid communications or can be utilized externally in free space communication channel.

Future works promise novel modulation/demodulation methods for generating data by optimizing geometry and material selection with specific colors and donor-acceptor pair arrays.

In addition, nanophotonics is another important area where the proposed device as a VLC modulator promises novel optical devices such as in applications utilizing single photon devices, quantum communications, plasmonics and electro-optic modulator structures. A simple, nanoscale and hybrid acousto-optic VLC modulator is designed without complicated device architecture and potential with high speed modulation capability [25]. The proposed system design is a future promising VLC transmitter with significantly many application areas.

http://dx.doi.org/10.5772/intechopen.73618

5. Conclusion

In this chapter, VFRET mechanism-based nanoscale acousto-optic sensor, acousto-optic wireless communication modulator and transducer converting the vibrations of multi-layer graphene resonator to multi-color photon emission are described. Graphene resonators achieve vibration frequencies ranging from acoustic to ultrasound ranges while significant advantages of graphene such as lightweight and 2D planar structure, large Young's modulus, low residual stress and large breaking strength. The device structure combined with QDs includes unique advantages of broad absorption spectrum, large cross-sections, tunable emission spectra, size dependent emission wavelength, high photochemical stability and improved quantum yield. Hybrid nanoscale acousto-optic system design promises important applications in sensing and communications for in-body networks and WBANs, space and interplanetary applications, microfluidics and VLC-based systems.

Acknowledgements

This work is supported by Vestel Electronics Inc., Manisa, Turkey.

Author details

Burhan Gulbahar[1]* and Gorkem Memisoglu[2]

*Address all correspondence to: burhan.gulbahar@ozyegin.edu.tr

1 Department of Electrical and Electronics Engineering, Applied Research Center of Technology Products, Ozyegin University, Istanbul, Turkey

2 Vestel Electronics Inc., Organize Sanayi Bolgesi, Manisa, Turkey

References

[1] Castallenos-Gomez A, Singh Van der Zant HS, Steele GA. Mechanics of freely suspended ultrathin layered materials. Annalen der Physik. 2015;**527**:27-44. DOI: 10.1002/andp.201400153

[2] Ferrari AC et al. Science and technology roadmap for graphene, related two-dimensional crystals, and hybrid systems. Nanoscale. 2015;**7**:4598-4810. DOI: 10.1039/C4NR01600A

[3] Memisoglu G, Gulbahar B. Acousto-optic tagging and identification, PCT/EP409508, Patent Application. June 2017

[4] Gulbahar B, Memisoglu G. Nanoscale optical communications modulator and acousto-optic transduction with vibrating graphene and resonance energy transfer. In: Proc. of the IEEE ICC 2017 Selected Areas in Communications Symposium Molecular, Biological and Multi-Scale Communications Track; 21-25 May 2017; France. IEEE; 2017. DOI: 10.1109/ICC.2017.7997036. http://ieeexplore.ieee.org/document/7997036/

[5] Gulbahar B, Memisoglu G. CSSTag: Optical nanoscale radar and particle tracking for inbody and microfluidic systems with vibrating graphene and resonance energy transfer. IEEE Transactions on NanoBioscience. 2017;**16**:905-916. DOI: 10.1109/TNB.2017.2785226

[6] Gulbahar B, Akan OB. A communication theoretical modeling of single-layer graphene photodetectors and efficient multireceiver diversity combining. IEEE Transactions on Nanotechnology. 2012;**11**:601-610. DOI: 10.1109/TNANO.2012.2187068

[7] Gulbahar B. Theoretical modeling of KHz to THz simultaneous energy harvesting and magneto-inductive communications with molecular magnets on vibrating graphene [Internet]. 2017. Available from: https://faculty.ozyegin.edu.tr/burhangulbahar/publications/ [Accessed: 2017-12-06]

[8] Gulbahar B, Memisoglu G. Acousto-optic transducer, array and method. PCT/EP2017/054408, Patent Application. July 2017

[9] Sevim S, Memisoglu G, Varlikli C, Dogan LE, Tascioglu D, Ozcelik S. An ultraviolet photodetector with an active layer composed of solution processed polyfluorene:Zn0.71Cd0.29S hybrid nanomaterials. Applied Surface Science. 2014;**305**:227-234. DOI: 10.1109/LPT.2014.2384532

[10] Ha T et al. Probing the interaction between two single molecules: Fluorescence resonance energy transfer between a single donor and a single acceptor. Proceedings of the National Academy of Sciences. 1996;**93**:6264-6268. DOI: PMC39010

[11] Kuscu M, Akan OB. Multi-step FRET-based long-range nanoscale communication channel. IEEE Journal on Selected Areas in Communications. 2013;**31**:715-725. DOI: 10.1109/JSAC.2013.SUP2.1213004

[12] Wojcik K, Solarczyk K, Kulakowski P. Measurements on MIMO-FRET nano-networks based on Alexa Fluor dyes. IEEE Transactions on Nanotechnology. 2015;**14**:531-539. DOI: 10.1109/TNANO.2015.2415201

[13] Shivkumar MA, Inamdar (Doddamani) LS, Rabinal MHK, Mulimani BG, Advi Rao GM, Inamdar SR. FRET from CdSe/ZnS core-shell quantum dots to fluorescein 27 dye. Open Journal of Physical Chemistry. 2013;**3**:40-48. DOI: 10.4236/ojpc.2013.31006

[14] Chou KF, Dennis AM. Förster resonance energy transfer between quantum dot donors and quantum dot acceptors. Sensors. 2015;**15**:13288-13325. DOI: 10.3390/s150613288

[15] Rosenthal SJ, Chang JC, Kovtun J, McBride R, Tomlinson ID. Biocompatible quantum dots for biological applications. Chemistry and Biology. 2011;**18**:10-24. DOI: 10.1016/j.chembiol.2010.11.013

[16] Gulbahar B. Theoretical analysis of magneto-inductive THz wireless communications and power transfer with multi-layer graphene nano-coils. IEEE Transactions on Molecular, Biological, and Multi-Scale Communications. 2017;**3**:60-70. DOI: 10.1109/TMBMC.2017.2655022

[17] Huang L et al. Ultra-low power sensor design for wireless body area networks: Challenges, potential solutions, and applications. JDCTA. 2009;**3**:136-148. DOI: 10.1.1.653.293

[18] Kanai H et al. Transcutaneous measurement and spectrum analysis of heart wall vibrations. IEEE Transactions on Ultrasonics, Ferroelectrics, and Frequency Control. 1996; **43**:791-810. DOI: 10.1109/58.535480

[19] Gulbahar B, Memisoglu G. Implementable medical device and intra-bone wireless communication system and methods. EP17172207.7, EPO Patent Application. May 2017

[20] Deisseroth K. Optogenetics. Nature Methods. 2011;**8**:26-29. DOI: 10.1038/nmeth.f.324

[21] Slater D, Ridenoure RW. Passive remote acoustic sensing in aerospace environments. In: AIAA SPACE 2015 Conference and Exposition; 2015. p. 4661. DOI: 10.2514/6.2015-4661

[22] Smal I, Loog M, Niessen W, Meijering E. Quantitative comparison of spot detection methods in fluorescence microscopy. IEEE Transactions on Medical Imaging. 2010;**29**:282-301. DOI: 10.1109/TMI.2009.2025127

[23] Shen H, Tauzin LJ, Baiyasi R, Wang W, Moringo N, Shuang B, Landes CF. Single particle tracking: From theory to biophysical applications. Chemical Reviews. 2017;**117**:7331-7376. DOI: 10.1021/acs.chemrev.6b00815

[24] Rajagopal S, Roberts RD, Lim SK. IEEE 802.15.7 visible light communication: Modulation schemes and dimming support. IEEE Communications Magazine. 2012;**50**(3):72-82. DOI: 10.1109/MCOM.2012.6163585

[25] Kim YT et al. Synthesis of a CdSe-graphene hybrid composed of CdSe quantum dot arrays directly grown on CVD-graphene and its ultrafast carrier dynamic. Nanoscale. 2013; **5**:1483-1488. DOI: 10.1039/c2nr33294a