Acharya J. C. Bose as Pioneer for Some Modern Phenomena and Devices in Electronics and Photonics

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Acharya J. C. Bose as Pioneer for Some Modern Phenomena and Devices in Electronics and Photonics

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Index Terms—Galena detector, Semiconductor device, IR detector, light tunneling, chiral metamaterial, memristor, photonic crystal, superlattice

Introduction

ACHARYA Jagadish Chandra Bose, FRS, a Physicist cum Botanist, born on November 30, 1858 in the undivided Bengal Province of British India, is the father of modern research in India. The salutation Acharya is a Sanskrit word, meaning a Guru whose preachings are to be followed. Most Indians prefer to call him Acharya, instead of commonly used salutation Sir in Western World. After obtaining First Arts and Bachelor of Arts degrees of the Calcutta University from the St. Xavier’s College, Calcutta, he went to England to study medicine. However, his ill health led him to give it up. He then joined Christ College of the University of Cambridge and obtained Tripos in Natural Science from there and concurrently the B.Sc. degree from the London University. Thereafter, he returned to India and joined Presidency College, Calcutta. As a protest to his significantly less salary compared to his European colleagues, he did not accept his salary for three years. After his salary issue was settled, he started research in a makeshift lab in his college. With his indigenously developed experimental set up, he conducted several experiments in physical sciences during 1895-1901, and published his research in different journals, notably in Proc. Royal Soc., London. Bose’s research after 1901 focused on botany, in particular on plant physiology. In 1917, he was conferred with knighthood and in the same year he also established Bose Institute, a premiere research institution in India. He became FRs, London in 1921. He breathed his last on November 23, 1937.

Bose’s biography, research contributions in both Physics and Plant Physiology are well documented, out of which only a few papers are cited here [1-11]. Bose’s paper in Physical Science are contained in [12].

Bose’s most notable work in physical sciences, performed during the short period 1895-1901, and widely discussed till today, is his microwave transmission experiments [1-11]. In his 1895 public demonstration in Calcutta, he used EM waves to ring a bell and fire gunpowder in a remotely located place far away from the source. Invited by Lord Rayleigh, he demonstrated his microwave experiments in the Royal Institution, London, and other places. In his lectures there, Bose predicted emission of EM radiation from the Sun, which was indeed detected in 1942 [4]. His galena detector [13] is recognized by Pearson and Brattain [14] as the first semiconductor device which got further confirmation in later publications [1]. Many of the components he developed for microwave communication, such as, horn antenna, waveguides, etc, are unique and followed and refined by many researchers in the coming decades. Emerson [4] also pointed out Bose’s pioneering work on double prism attenuator and its modified form in the multiple prism receiver developed by National Radio Astronomy Observatory installed in Kitt’s Park, Tuscon, Arizona USA [15]. Mitra [16] mentioned Bose’s jute polarizer as the first specimen used for analog crystallography. Ghoshal [17] has recently written a tutorial on Bose’s double prism experiments using classical ray optic approach. Emerson also mentioned Bose’s use of twisted jute bundle and a railway time table as polarizers.

The purpose of the present paper is to examine Bose’s pioneering experiments in a more current perspective that have not been discussed in the earlier publications. The present author has identified a few of Bose’s experiments and tried to relate these to modern electronics and photonics. These experiments are still considered as the first by lead expert workers in the respective areas. These novel works have far reaching consequences to motivate further research even over a century, and in addition in areas developed over the last two decades of the present millennium. Bose’s novel research activities are cited in different publications, but are scattered and are less publicized.

The present paper therefore proposes to prepare, as far as possible, a compilation of the less publicized but otherwise recognized pioneering contributions of Bose in the area of...
modern electronics and photonics. The list of such work includes 1) the first demonstration of IR detection by galena detector, 2) light tunnelling and consequent work on frustrated total internal reflection, analogous to quantum mechanical tunnelling and superluminal propagation, 3) jute polarizer as the first chiral metamaterial and 4) the hysteresis in the I-V curve of Bose’s coherer as the first signature of the memristors, the fourth circuit element. In this connection, the original experimental arrangement and findings by Bose in each work, along with a brief introduction to the physical understanding of the phenomenon are presented and his relevant publications are cited. The comments and observations of the experts recognizing Bose’s initiation of investigation in each area, are included. Furthermore, the current application areas of the recently developed fields of electronics and photonics with reference to Bose’s research are pointed out. The present paper also points out the structural similarity between the railways time table having thin tin foils inserted between pages, as used by Bose as a polarizer and both the one dimensional photonic crystal (PhC) and the semiconductor superlattice (SL). It then attempts to examine the anisotropic behaviour of all the three structures. At the end a comment made by Sir Neville Mott, that Bose was at least 60 years ahead of his time, and in fact he anticipated the existence of p-type and n-type semiconductors, already examined in [11] will be mentioned.

The paper is organized as follows. Sec. II gives a sketch of the experimental set up by Bose, describing the function of the components. Sec. III describes Bose’s work on coherer or detector for IR waves. Sec. IV narrates his light tunneling experiment and the relevance to modern research. Sec. V relates jute polarizer with chiral metamaterials. Sec. VI introduces memristors and points out the commonality of hysteresis in both Bose’s coherer and memristor. Sec VII first points out the similarities of time table polarizer, 1D PhC and SL. Sec. VIII examines Mott’s remark. Sec. IX concludes the paper.

II. BOSE’S EXPERIMENTAL SET UP

The schematic diagram of the experimental set up designed and established by Bose is shown in Fig. 1. It has been redrawn using Fig. 17 of the paper published by Bose in the Friday Evening Discourse, Royal Institution [18]. For further details see P Bhattacharyya and M H Engineer, Emerson and A Maitra.

In the left, the light or electromagnetic source (S) is shown, which was basically a spark gap terminal generating burst of EM waves. The graduated circular pedestal (P) serves as the platform to support the specimen on which the EM radiation falls. The specimen under test (T) may be a twisted jute polarizer or a double prism assembly or mirrors of different shapes. The EM wave coming out of the specimen is collected by a collecting funnel or a pyramidal horn (H) connected to an assembly consisting of a coherer or detector (D). The detector is energized by a cell (C) and a potentiometric arrangement consisting of a rheostat (Rh); a galvanometer (G) connected to the circuit measures the signal strength. The detector system can be rotated by an arrangement (R) to record the signal coming out of different directions of the specimen.

III. BOSE’S WORK ON DETECTORS

Bose’s detector in his microwave communication experiment was first a coherer, which consisted of metallic particles filling a container having two electrodes. He observed the nonlinear current-voltage characteristics, typical of a detector, and found an elegant method of decohering action. He then experimented with a metal contact hardly pressed on another metal and other substances like metals, metalloids, and other materials like galena, tellurium etc. Finally, he invented the metal cat whisker- Galena crystal detector, for which he filed patent application in 1901. The work is well documented.

In connection with his work on coherer, Bose introduced positive and negative coherers. As noted by Mitra, the metal plate might be oxidized to become p-type or n-type semiconductor. A thorough analysis of working principle of coherers and their relevance to p/n type semiconductor is now needed and some observations will be presented in this paper in Sec. VII.

Bose called his detector as Tejometer (Tej means energy). His detector was capable of detecting EM waves of all frequencies, including infrared. As noted by Rogalsky [20], he is considered as the pioneer for IR detector.

IV. LIGHT TUNNELLING

The second pioneering work by Bose is described in his paper entitled “The influence of thickness of air-space on total reflection of electric radiation” [21]. He first used two semi cylinders separated by a small air gap. There was total internal
reflection when the air gap was wide; however, with smaller gap thickness, he found a transmitted component, complementary to the reflected one. The critical thickness for the onset of transmission depended on the angle of incidence.

A transmitted component of light was also observed by Bose in his double prism experiment, the schematic of which is given in Fig. 3. The double prism is separated by an air gap, the thickness of which can be changed. EM radiation is incident on the left prism. It then strikes the face at an angle of 45 which exceeds the critical angle and thus light is totally reflected as long as the air gap is wide. However, when the thickness of the air gap is reduced below the critical thickness, there is transmission of wave, as shown in Fig. 3. Bose changed the wavelength of the source and found that the critical thickness differs for different wavelengths. Insertion of a dielectric in the air gap also changed the value of critical thickness. Details of other experiments and results may be found in the paper, as well as in [17].

This work by Bose records the first observation of frustrated total internal reflection [22-24].

![Fig. 3: The double prism system used by Bose to demonstrate first the frustrated total internal reflection (FTIR).](image)

The phenomenon FTIR may be explained from both the ray optic theory and the wave theory. Fig. 3 may be used to discuss FTIR by the ray optic theory. The incident ray entering into the prism having RI $n_1$ strikes the interface at point A. It then enters into the air gap, penetrates some distance (not shown in figure) and then retraces back to enter into the left prism as the reflected ray at point B. The shift AB is known as Goos- Hanschen shift, after the persons observed first experimentally in 1914 [25]. This description applies when the air gap separating the right prism from the left prism is quite thick. However, when the separation is small, a part of the ray leaking into the gap reaches the right prism at point C and travels as the transmitted ray.

In later years, the work has been recognized as the first work on light or photon tunnelling [22, 26-28]. In the following paragraphs, we make an attempt to draw parallelism between the classical FTIR, viewed in the light of EM wave theory and a quantum mechanical wave function of electrons or other subatomic particles, both of which exhibit quantum mechanical tunneling. This is illustrated in Fig. 4.

The top part of Fig. 4, 4(a), illustrates the FTIR phenomenon by considering an incident light I striking the interface between a dielectrics of RI $n_1$ and another dielectric of RI $n_2$ of thickness $d$ separating the first dielectric from a similar dielectric. The arrangement is similar to that in the double prism experiment. The incident (I), reflected (R) and transmitted (T) rays are shown. The behaviour of EM waves in the three media as shown in (a) is shown in Fig. 4(b) as a function of distance $x$. The sharp change in refractive index from $n_1$ of the prism to $n_2$ of air is indicated by the blue line and the RI profile is well-like. The variation of the electric field amplitude of EM wave, $A(x)$, in the structure is obtained by solving the Helmholtz equation satisfying the boundary conditions at the two interfaces. The amplitude of EM wave in the lower index dielectric in the middle (air gap in double prism experiment) is decaying, characteristic of an evanescent wave. The oscillatory nature of the amplitude in the two higher index dielectrics (two prisms) signifies that the waves are propagating.

Although the wave nature of EM radiation has been known earlier, it took more than a century to discover that electrons and other quantum particles also possess similar wave like properties. The phenomenon of quantum mechanical tunneling received attention thereafter, which however has any classical analog.

![Fig. 4: Illustration of light tunnelling and quantum mechanical tunnelling.](image)
Figs. 4(c) and (d) illustrate the quantum mechanical tunnelling phenomena. In Fig. 4(c), a thin potential barrier \( V_0 \) is shown to exist upon which a particle, say an electron is incident (I). The energy of electron \( E \) is less than the barrier potential \( V_0 \). Classically, the electron cannot surmount the barrier to come to the other side. However, if the barrier is thin enough and height large, electron can tunnel through the barrier resulting in a transmitted (T) and a reflected (R) component. The wave nature of the electron is obtained by solving Schrödinger equation satisfying proper boundary conditions at the two walls of the barrier. The nature of the wave function, \( \Psi(x) \), in the three regions is depicted in Fig. 4(d). As indicated the wave functions are oscillatory outside the barrier, but decay within it. It is also known that the barrier must be thin enough to allow the electron to tunnel through it. Notice the similarity between light tunneling and particle tunneling.

Light or EM wave tunneling has important applications. One example is a directional coupler in which two waveguides 1 and 2 are placed in close proximity. EM wave launched into waveguide 1 leaks into the second waveguide, and under suitable condition EM energy fed into guide 1 is completely transferred to guide 2. There are many such passive devices in which the evanescent coupling of EM waves leads to desired functionalities. [29].

It has been long believed that tunneling is an instantaneous phenomenon. Based on this, the velocity of light in thin insulator through which tunneling occurs, must exceed the value of \( 3 \times 10^8 \text{ m/s} \) [22, 26,27]. Such conjecture of superluminal propagation of light led to extensive work in this area, and controversies over tunnelling time [8]. Some recent work however pointed out that the tunneling time must be redefined and appears to settle the controversy [28].

It is evident, therefore, that Bose’s pioneering double prism experiment has given birth to many novel phenomena in physical science as well as devices in photonics.

V. CHIRAL METAMATERIAL

Bose used twisted jute as shown in Fig. 5, as the polarizer for his famous microwave communication experiment [30]. His jute polarizer is viewed by many[31-33] today to be the first example of artificial material or metamaterial, particularly as chiral metamaterial.

Solymar and Walsh [31] observed In 1998, Jagadish Chunder Bose proposed twisted jute as an artificial material. He showed that such a material would rotate the polarization of an electromagnetic wave. We would call it now-a-days an artificial chiral material.

The Guest Editorial by Wegener and Zheludev [32] for a special issue entitled Artificial Chiral Materials runs like this: In 1898 Acharya J C Bose wrote ‘In order to imitate the rotation by liquids like sugar solutions, I made elements of “molecules” of twisted jute, of two varieties, one kind being twisted to the right (positive) and the other twisted to the left (negative). The twisted structure produces an optical twist of the plane of polarization’

Fig. 5: photograph of twisted jute polarizer used by Bose, as the first example of artificial chiral metamaterial. Fig. 12 in [19] © IEEE

The Editors also noted that this paper reporting experimental microwave tests on the optical activity of the artificial chiral medium, was the first publication on what has now become a flourishing and dynamic field of metamaterials.

Iyer et al [33] also mentioned the work of Bose as the first one in artificial dielectrics.

The concept of metamaterial was given by Veselago in 1967 [34] who predicted negative refraction by such materials. The material must have both negative permittivity and permeability to produce negative refraction. Later Pendry et al [35] proved that a periodic structure using a slip ring resonator and a straight wire as the basic element would form the desired structure. The negative refraction was then achieved by Smith and coworkers [36]. Later, it has been established that negative refraction is also the characteristics of certain anisotropic materials, called chiral metamaterial [37,39].

In a natural crystal, the atoms or molecules are arranged in a regular fashion and maintain a fixed interatomic distance or lattice constant \( a \). In order to study the properties, EM wave having wavelength of the order of \( a \) is needed. For crystals, the waves are X-rays and hence the name X-ray crystallography is in use. In twisted jute, each fiber replaces an atom in a crystal (molecule as stated by Bose). However, the distance between fibers is quite large, \( \approx \text{mm} \). Thus in order to study and control the EM properties, mm wavelengths, longer than X-ray wavelengths, are needed. Mitra [16] called this Analog Crystallography introduced by Bose.

Artificial structures like metamaterials and their twodimensional form, the metasurfaces, have assumed an important role in modern electronics and photonics. The structures form perfect lens [39], resonators and other photonic devices of recent and near future applications. As a perfect reflector, the structures are believed to make invisibility cloaks. See Iyer et al [33] and Basu et al [39] for details and useful references.

VI. MEMRISTOR

There are three passive circuit elements, resistor (R), capacitor (C) and inductor (L), known to everybody in science. Leon Chua, using four Maxwell equations and symmetry arguments, conceived and proposed the existence of the fourth passive circuit element named as memristor [40]. However, unlike \( R \), \( L \) and \( C \), memristors cannot be realized in macro-sized
forms. The first reported memristor device used transition metal oxides [41] and later chalcogenides, perovskites, oxides with valence defects, or a combination of an inert and an electrochemically active electrode.

Gandhi et al. [42] defined a passive memristor in the following way. It is a two-terminal device having no internal power source and when an appropriate current or voltage signal is applied to its terminals, it switches between two resistance states. Its I-V characteristics show a pinched hysteresis loop between two resistance states. This pinched hysteresis loop serves as the fingerprint of the memristor.

Fig.6: The I-V characteristics exhibited by the coherer used by Bose subjected to cyclic changes in the Electromotive force. In each curve, the right and left hand parts are due, respectively, to increasing and decreasing EMF. Redrawn from Fig. 55 (p.241) in [44].

Gandhi et al [42] traced back the early investigations and established that the pinched hysteresis loops exhibited by Bose’s coherer [43, 44] and the cat’s whisker detector is the first evidence of memristive properties. An example of the characteristics obtained by Gandhi et al. for a cat’s whisker diode is given in Fig. 7.

Fig.7: Qualitative variation of current versus voltage of a typical cat’s whisker diode as obtained by Gandhi et al. A0-A3 correspond to different intervals for cyclic EMF. Redrawn from Fig. in Gandhi et al [42] © IEEE.

Roy and Hart [10] after presenting a life sketch of J. C. Bose, mentioned his pioneering research in memristor action as reported by Gandhi et al and obtaining hysteresis loop in the I-V characteristics of Bose’s coherer.

Roy and Hart [10] recalled that Just a few years before Bose began to study coherers, the term hysteresis had been coined (it literally means “lagging behind”) to describe the behavior of magnetization in iron in response to an externally applied magnetic field. They also mentioned that Bose’s lecture in Glasgow in 2001 on hysteresis in conductivity of metal particles (including iron filings) in response to an applied voltage and showed that the resistance depended on the history and extent of the voltage applied. His device acted very much as a resistor, but the value of resistance depended on the entire history of the current.

VII. PHOTONIC BAND GAP AND SUPERLATTICE STRUCTURES

In all the earlier sections, the work by Bose as the first demonstration of the respective physical phenomenon has been identified by experts in the fields. In this section, a specific work by Bose as the first example of photonic band gap structure or a semiconductor superlattice will be pointed out.

Bose replaced his twisted jute polarizer by a railway time table available at his time, the Bradshaw time table, in which thin foils of tin were interspersed between two paper sheets throughout the time table. The photograph of such arrangement is shown in Fig. 8. Bose could polarize the EM wave by using these multilayered structures. Even without tin foils, that is having air gaps between the sheets of papers, the same polarizing action was observed by him. The multilayered structure thus exhibited anisotropy, passing light along the direction normal to the planes of the papers, but stopping light along the perpendicular direction.

Fig.8: The photograph of the railway time table in which thin tin foils were inserted between pages and used as a polarizer. Fig. 10 in [19] © IEEE

It is amply clear that the time table polarizer that Bose used consisted of two dielectrics (tin and paper or air and paper) arranged periodically as illustrated in the upper part of Fig. 9. The corresponding variation of RI is shown in the lower part.

A few decades later, properties of a multilayered structure made of two different dielectrics were investigated. These structures,
known as Bragg mirrors and Bragg reflectors, are in continuous use in modern semiconductor lasers, particularly in Vertical Cavity Semiconductor Lasers (VCSELs) [45]. The Bragg mirrors consist of alternate thin layers of GaAs and AlAs, to cite a specific example. These are one dimensional periodic structure.

Fig. 9: Schematic diagram showing the structure of a 1D photonic crystal having alternate layers of two different dielectrics, A and B, separated by d (upper part). The period variation of permittivity along the structure is shown in the lower part. A semiconductor superlattice has a similar structure as of a 1D PhC, in which alternate layers comprise two different semiconductors, such as GaAs and AlAs.

Studies on two-dimensional and three-dimensional periodic structures involving different pairs of dielectrics, started later in 1980’s [46]. Since then, a lot of research and development took place in the fabrication, characterization and applications. The structures are now called Photonic Band Gap structures and find extensive use in modern photonics and communication.

Work on similar multilayered structures using two different semiconductors, called superlattices, started since 1970’s and have found extensive applications in photonics [47].

It is to be noted that both PBG and SL structures show anisotropy in their propagation characteristics as found experimentally. This behaviour is expected from the calculated dispersion characteristics of both the structures. In case of PBG the dispersion relation is a plot of the frequency of the propagating EM wave versus the wave number or wave vector. For SL structure it is the plot of energy of electrons versus the wave vector of the propagating electron wave. This means the propagation of EM waves in PBG and of electron waves in SL, follow different patterns or possess anisotropy similar to that exhibited by the time table in Bose’s experiment.

To the best of our knowledge, such parallelism between Bose’s time table and PBG or SL has not been drawn earlier.

VIII. SEMICONDUCTOR CONDUCTIVITY TYPE

This section will discuss about an oft-quoted comment on Bose by Sir Neville Mott, Nobel laureate in physics in 1977 for his work on semiconductor and solid state physics. He remarked that Bose was at least 60 years ahead of his time and in fact he anticipated the existence of n-type and p-type semiconductors. This remark appeared in the papers by Mitra [16], is mentioned in the title page of the website of the Bose Institute [48], quoted by Johnson [49], Emerson [19], and D. Bose [50]. Subsequently, many popular articles, journal publications and books mentioned the comments by Mott.

D. Bose [50] identified the time and the person to whom Mott made this comment. However, no clue was given about how Mott arrived at his conclusion. He made an attempt to justify the statement by Mott on the anticipation of conductivity type by Bose. A more elaborate study on this topic has recently been conducted by the present author [11].

IX. CONCLUSION

Sir J. C. Bose’s first demonstrated microwave communication over moderate distances. This work and his galena detector as the first reported semiconductor device are well documented. A few of his other pioneering experiments are less known to present workers, however, the discussion of which is the main focus of this paper. Bose’s galena detector was the first IR detector. His double prism experiment led to the concept of frustrated total internal reflection and light tunnelling. This led to development of waveguides, directional couplers and extensive research to settle the controversy on tunnelling time and superluminal transmission. His twisted jute polarizer gets credit from workers as the first example of chiral metamaterial. His observed hysteresis in I-V curve of coherers is considered as the first signature of memristor, the fourth circuit element. His polarizer using a railway time table is the first example of multi-layered dielectrics, later known as photonic crystals and superlattices. All these activities are discussed briefly including recent comments and citations on these. At the end an oft quoted remark by Mott on his anticipation of conductivity type of semiconductors is examined briefly.

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