The Work of Jagadis Chandra Bose: 100 Years of Millimeter-Wave Research

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Abstract—**Just 100 years ago, J. C. Bose described to the Royal Institution, London, U.K., his research carried out in Calcutta, India, of millimeter wavelengths. He used waveguides, horn antennas, dielectric lenses, various polarizers, and even semiconductors at frequencies as high as 60 GHz. Much of his original equipment is still in existence, currently at the Bose Institute, Calcutta, India. Some concepts from his original 1897 papers have been incorporated into a new 1.3-mm multibeam receiver now in use on the National Radio Astronomy Observatory (NRAO) 12-m telescope.**

Index Terms—**History, microwave technology, millimeter-wave technology.**

Fig. 1. Bose at the Royal Institution, London, U.K., January 1897 (Photograph from [13]).

I. Introduction

JAMES Clerk Maxwell's equations predicting the existence of electromagnetic radiation propagating at the speed of light were made public in 1865. In 1888, Hertz had demonstrated generation of electromagnetic waves, and that their properties were similar to those of light [1]. Before the start of the 20th century, many of the concepts now familiar in microwaves had been developed [2], [3], including the cylindrical parabolic reflector, dielectric lens, microwave absorbers, the cavity radiator, the radiating iris, and the pyramidal electromagnetic horn. Round, square, and rectangular waveguides were used, with experimental development anticipating by several years Rayleigh's 1896 theoretical solution [4] for waveguide modes. Many microwave components in use were quasi-optical—a term first introduced by Lodge [5]. In 1897, Righi published a treatise on microwave optics [6].

Hertz had used a wavelength of 66 cm. Other post-Hertzian pre-1900 experimenters used wavelengths well into the short centimeter-wave region, with Bose in Calcutta [7], [8] and Lebedew in Moscow [9] independently performing experiments at wavelengths as short as 5 and 6 mm.

II. The Research of Bose

J. C. Bose [10]-[12] was born in India in 1858. He began his education in India, until he went to the U.K. in 1880 to study medicine at the University of London. Within a year he moved to Cambridge to take up a scholarship to study Natural Science at Christ's College Cambridge. One of his lecturers at Cambridge was Prof. Rayleigh, who clearly had a profound influence on his later work. In 1884, Bose was awarded a B.A. degree from Cambridge, along with a B.Sc. degree from London University. Bose then returned to India, initially taking up a post as officiating professor of physics at Presidency College, Calcutta. Following the example of Lord Rayleigh, Bose made extensive use of scientific demonstrations in class, where he is reported as being extraordinarily popular and effective as a teacher. Many of his students at Presidency College were destined to become famous in their own right—e.g., S. N. Bose, later to become well known for the Bose–Einstein statistics.

The book by Sir Oliver Lodge, *Heinrich Hertz and His Successors*, impressed Bose. In 1894, he converted a small enclosure adjoining a bathroom in Presidency College into a laboratory. He carried out experiments involving refraction, diffraction, and polarization. To receive the radiation, he used a variety of different junctions connected to a highly sensitive galvanometer. He plotted in detail the voltage–current characteristics of his junctions, noting their nonlinear characteristics. He developed the use of galena crystals for making receivers, both for short-wavelength radio waves and for white and ultraviolet light. Patent rights for their use in detecting electromagnetic radiation were granted to him in 1904. In 1954, Pearson and Brattain [13] gave priority to Bose for the use of a semiconducting crystal as a detector of radio

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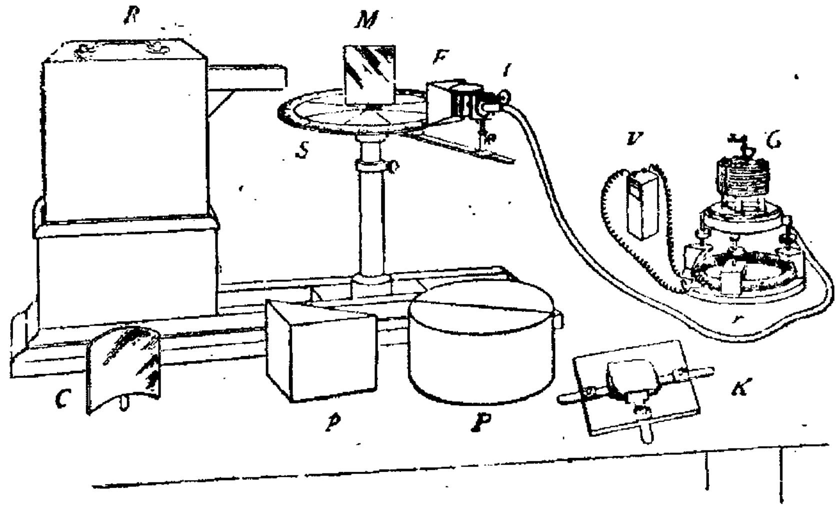


R, radiator ; S, spectrometer-circle ; M, plane mirror ; C, cylindrical mirror ; *p*, totally reflecting prism ; P, semi-cylinders ; K, crystal-holder ; F, collecting funnel attached to the spiral spring receiver ; *t*, tangent screw, by which the receiver is rotated ; V, voltaic cell ; *r*, circular rheostat ; G, galvanometer.

Fig. 2. Bose's apparatus demonstrated to the Royal Institution in 1897 [8]. Note the waveguide radiator on the transmitter (left), and that the "collecting funnel" (F) is, in fact, a pyramidal electromagnetic horn antenna, first used by Bose (Photograph from [8]).

waves. Sir Neville Mott, Nobel Laureate in 1977 for his own contributions to solid-state electronics, remarked [12] that:

> "J. C. Bose was at least 60 years ahead of his time"

and

> "in fact, he had anticipated the existence of p-type and n-type semiconductors."

In 1895, Bose gave his first public demonstration of electromagnetic waves, using them to remotely ring a bell and to explode some gunpowder. In 1896, the *Daily Chronicle* of the U.K. reported,

> "The inventor (J. C. Bose) has transmitted signals to a distance of nearly a mile and herein lies the first and obvious and exceedingly valuable application of this new theoretical marvel."

Popov in Russia was doing similar experiments, but had written in December 1895 that he was still entertaining the hope of remote signaling with radio waves. The first successful wireless-signaling experiment by Marconi on Salisbury Plain, U.K., was not until May 1897.

The 1895 public demonstration by Bose in Calcutta predates all these experiments. Invited by Lord Rayleigh, Bose reported on his microwave (millimeter-wave) experiments to the Royal Institution and other societies in the U.K. [8] in January 1897. The wavelengths he used ranged from 2.5 cm to 5 mm. In his presentation to the Royal Institution, Bose speculated [8, p. 88] on the existence of electromagnetic radiation from the sun, suggesting that either the solar or the terrestrial atmosphere might be responsible for the lack of success so far in detecting such radiation. Solar emission was not detected until 1942, and the 1.2-cm atmospheric-water vapor-absorption line was discovered during experimental radar work in 1944. Fig. 1 shows Bose at the Royal Institution, London, U.K., in January 1897. Fig. 2 shows a matching diagram, with a brief description of the apparatus.

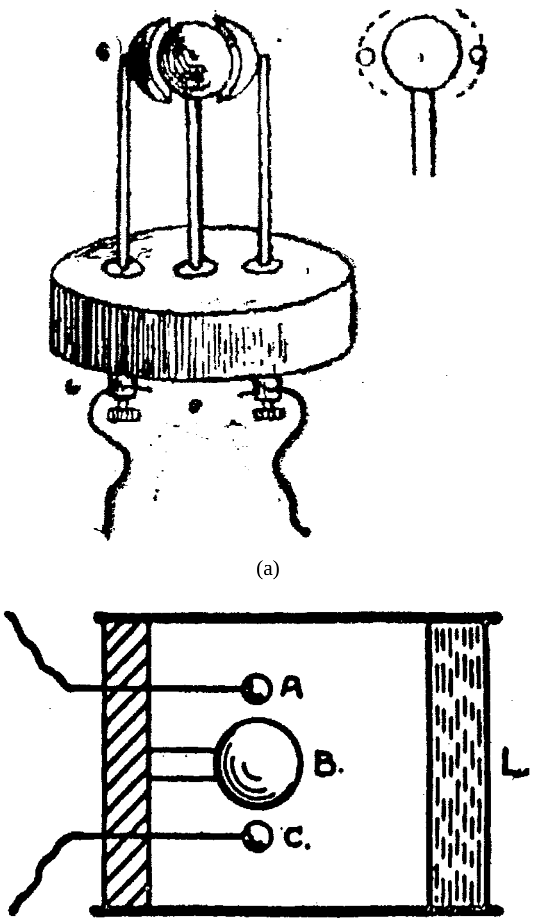
By about the end of the 19th century, the interests of Bose turned away from electromagnetic waves to response phenomena in plants; this included studies of the effects of electromagnetic radiation on plants, which is a topical field today. He retired from Presidency College in 1915, but was appointed Professor Emeritus. Two years later, the Bose Institute, Calcutta, India, was founded. Bose was elected a Fellow of the Royal Society in 1920. He died in 1937, a week before his 80th birthday. His ashes are in a shrine at the Bose Institute.

III. Bose's Apparatus

Bose's experiments were carried out at Presidency College, although for demonstrations he developed a compact portable version of the equipment, including transmitter, receiver, and various microwave components. Some of his original equipment still exists, currently at the Bose Institute. In 1985, the author was permitted by the Bose Institute to examine and photograph some of this original apparatus.

Fig. 3(a) shows Bose's diagram of one of his radiators used for generating 5-mm radiation.

Oscillation is produced by sparking between two hollow hemispheres and the interposed sphere. There is a bead of platinum on the inside surface of each hemisphere. For some experiments, a lens of glass or sulfur was used to collimate the radiation—the first waveguide–lens antenna. The lens was designed according to the refractive index measured by Bose at the wavelength in use. Fig. 3(b) shows Bose's drawing of such a radiator; the sparks occur between the two outer spheres to the inner sphere, at the focal point of the lens at the right.



(a)

(b)

Fig. 3. Bose's diagrams of his radiators. (a) The radiator used to generated 5-mm radiation (Photograph from [8]). (b) The arrangement with a lens at the exit of the waveguide [2]. In some designs the mounting stems for the outer spheres could be inclined to adjust the dimension of the spark gaps (Photograph from [2]).

Bose was able to measure the wavelength of his radiation with a reflecting diffraction grating made of metal strips [7].

Fig. 4 is a photograph of one of Bose's radiating antennas. The spark oscillations are generated inside the overmoded circular waveguide. A polarizing grid is built into the antenna, clearly visible at the radiating end of the waveguide.

Fig. 5 shows two of Bose's point contact detectors. In use, the detector would be placed inside an overmoded waveguide receiving antenna, very much like the transmitting antenna shown in Fig. 4, and with a matching polarizing grid.

Bose measured the *I–V* characteristics of his junctions; an example characteristic curve of a "single-point iron receiver" is shown in Fig. 6. The junction consisted of a sharp point of iron pressing against an iron surface, with pressure capable of fine adjustment. The different curves in Fig. 6 correspond to different contact pressures. Bose noted that the junction does not obey Ohm's law, and that there is a knee in the curve at approximately 0.45 V; the junction becomes most effective at detection of short wavelength radiation when the corresponding bias voltage is applied. He made further measurements on a variety of junctions made of different materials, classifying the different materials into positive or negative classes of substance. In one experiment, he noted that increasing the applied voltage to the junction actually decreased the resulting current, implying a negative dynamic resistance [14].

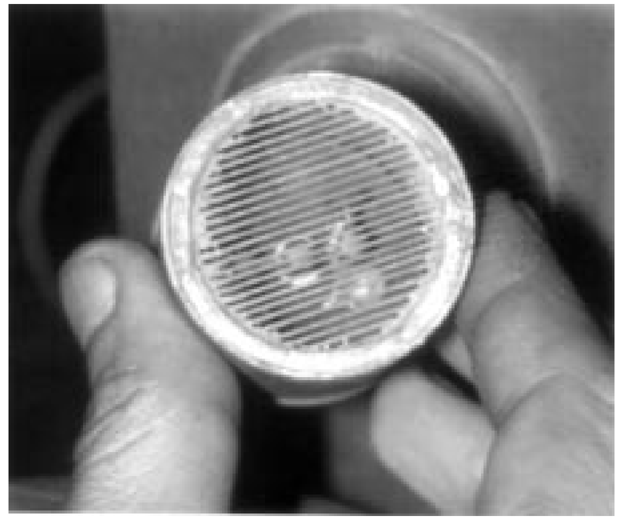


Fig. 4. One of Bose's transmitter antennas. Note the polarizing grid. The spark gap is just visible behind the grid.

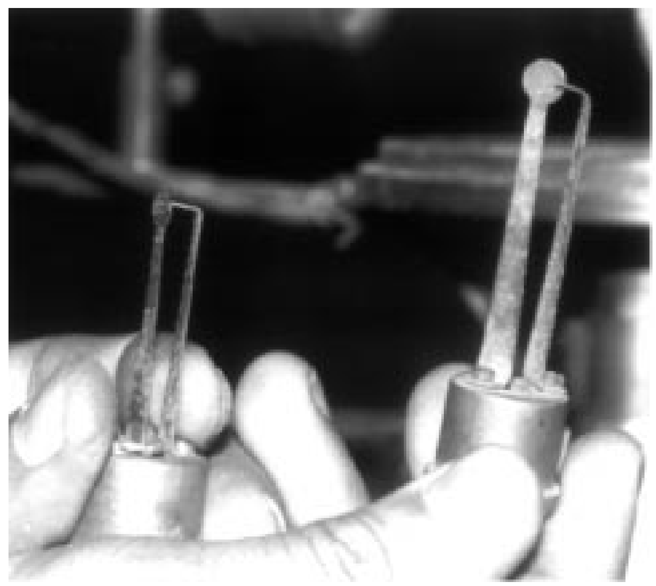


Fig. 5. Two of Bose's point contact detectors, removed from the receiving antenna.

Another of Bose's short-wavelength detectors is the spiral-spring receiver. A sketch of a receiver used for 5-mm radiation is shown in Fig. 7. The spring pressure could be very finely adjusted in order to attain optimum sensitivity. The sensitive surface of the 5-mm receiver was 1 cm $\times$ 2 cm. The device has been recently described [3] as a "space-irradiated multi-contact semiconductor (using the natural oxide of the springs)." A surviving, somewhat larger, spiral-spring receiver is shown in Fig. 8. The springs are held in place by a sheet of glass, seen to be partly broken in this example.

Fig. 9 is Bose's diagram of his polarization apparatus. The transmitter is the box on the left, and a spiral spring receiver

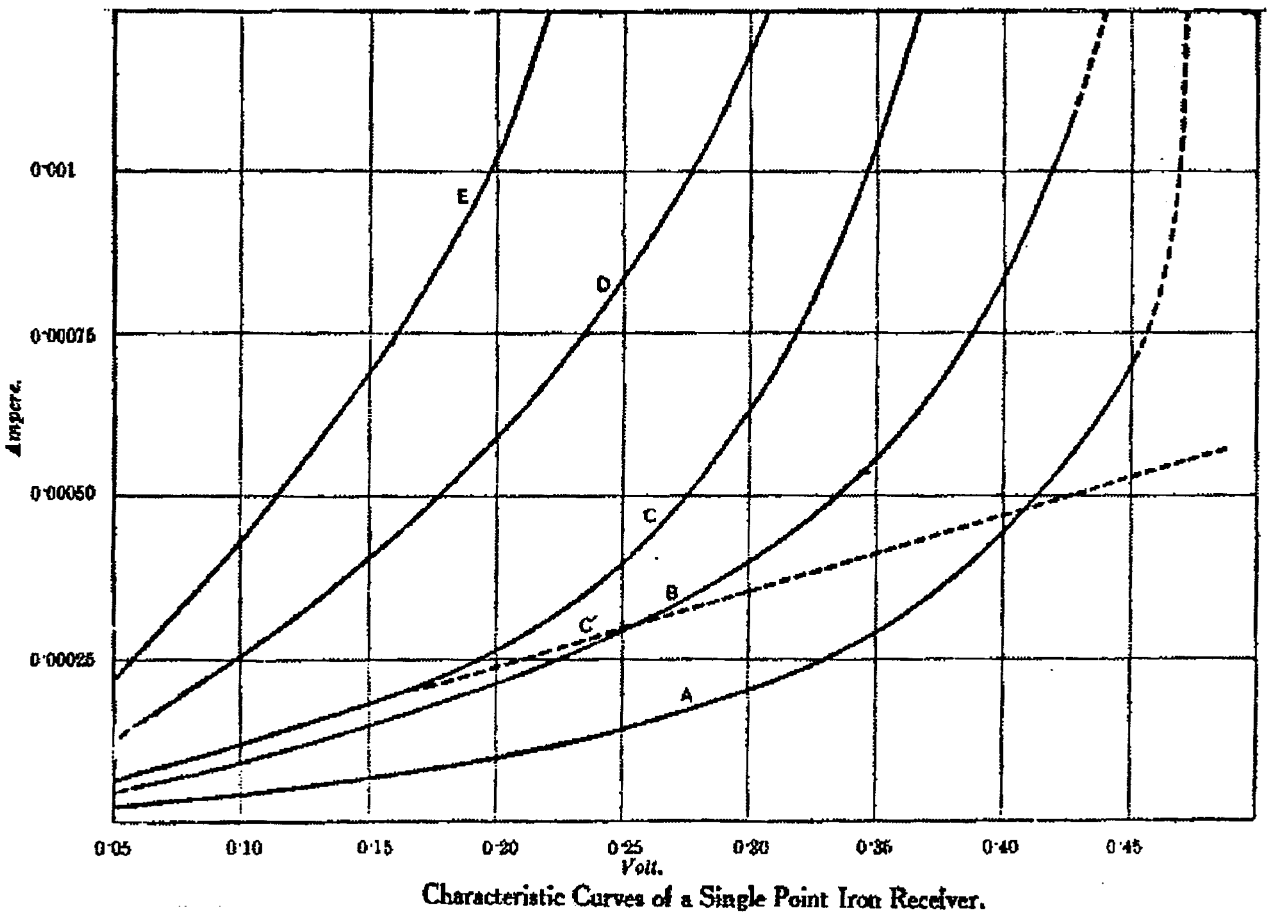


Fig. 6. The *I–V* characteristics measured by Bose for a single-point iron receiver. Note the similarity to modern semiconductor junctions, with a knee voltage of approximately 0.4 V. A, B, C, D, and E are different curves for different initial currents. C' is the curve for a constant rersistance (Photograph from [8]).

(R) is visible on the right. One of the polarizers used by Bose was a cutoff metal plate grating, consisting of a book (Bradshaw's *Railway Timetable*, Fig. 10) with sheets of tinfoil interleaved in the pages. Bose was able to demonstrate that even an ordinary book, without the tinfoil, is able to produce polarization of the transmitted beam. The pages act as parallel dielectric sheets separated by a small air gap.

Bose experimented with samples of jute in polarizing experiments. In one experiment, he made a twisted bundle of jute and showed that it could be used to rotate the plane of polarization. The modern equivalent component may be a twisted dielectric waveguide. He further used this to construct a macroscopic molecular model as an analogy to the rotation of polarization produced by liquids like sugar solutions. Fig. 11 shows Bose's diagram of the jute-twisted–fiber polarization rotator, and Fig. 12 is a photograph of a surviving twisted-jute polarizer at the Bose Institute.

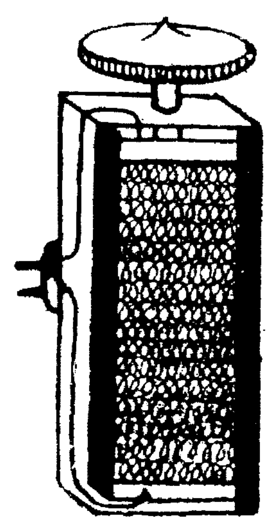


Fig. 7. Bose's diagram of his spiral-spring receiver used for 5-mm radiation (Photograph from [8]).

IV. The Double-Prism Attenuator

Bose's investigations included measurement of the refractive index of a variety of substances. He made dielectric lenses and prisms; examples of which are shown in Figs. 1 and 2.

One investigation involved measurement of total internal reflection inside a dielectric prism, and the effect of a small air gap between two identical prisms. When the prisms are widely separated, total internal reflection takes place and the incident radiation is reflected inside the dielectric. When the two prisms touch, radiation propagates unhindered through both prisms. By introducing a small air gap, the combination becomes a variable attenuator to incident radiation, illustrated in Bose's original diagram and shown in Fig. 13. Bose investigated this

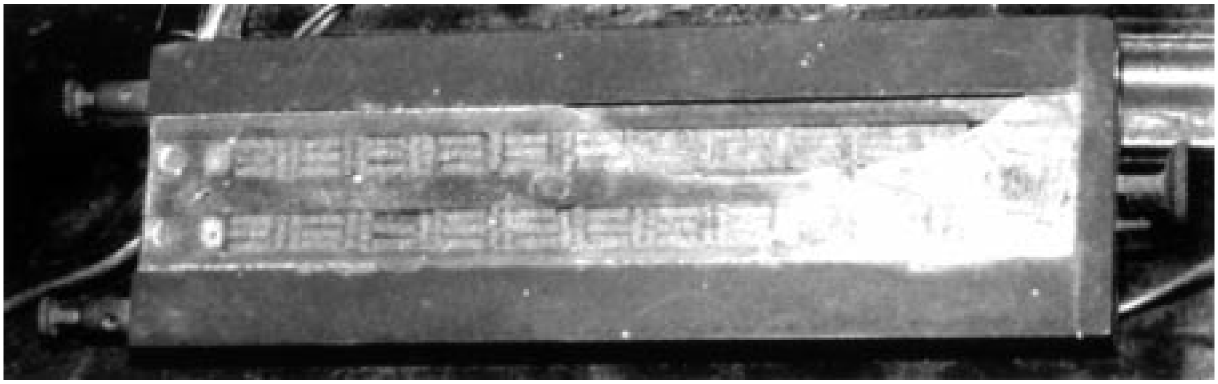


Fig. 8. One of Bose's free-space radiation receivers, recently described [3] as a "space-irradiated multi-contact semiconductor (using the natural oxide of the springs)." The springs are kept in place in their tray by a sheet of glass, seen to be partly broken in this photograph.

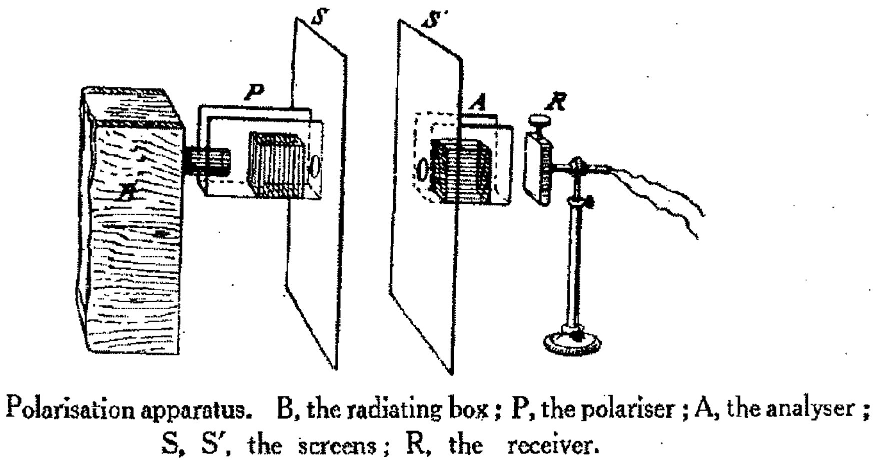


Fig. 9. Bose's diagram of his polarization apparatus. Note the spiral-spring receiver to the right (Photograph from [8]).

prism attenuator experimentally and his results were published in the *Proceedings of the Royal Society* in November 1897 [8]. Schaefer and Gross [15] made a theoretical study of the prism combination in 1910. The device has since been described in standard texts.

At the NRAO, a new multiple-feed receiver operating at a wavelength of 1.3 mm has recently been built and installed on the 12-m telescope at Kitt Peak [17]. The system is an eight-feed receiver, where the local oscillator is optically injected into the superconducting tunnel junction (SIS) mixers. With an SIS-mixer receiver, the power level of the injected local oscillator is critical. Each of the eight mixers requires independent local oscillator power adjustment. This is achieved by adjustable prism attenuators. Fig. 15 shows four of these eight prism attenuators installed on one side of the eight-feed system. This can be compared with Fig. 14, which is a photograph taken at the Bose Institute in 1985, showing an original prism system built by Bose.

V. Conclusion

Research into the generation and detection of millimeter waves and the properties of substances at these wavelengths was being undertaken in some detail 100 years ago in Calcutta, India, by Bose. Many of the microwave components familiar today—waveguide, horn antennas, polarizers, dielectric lenses and prisms, and even semiconductor detectors of electromagnetic radiation—were invented and used in the last decade

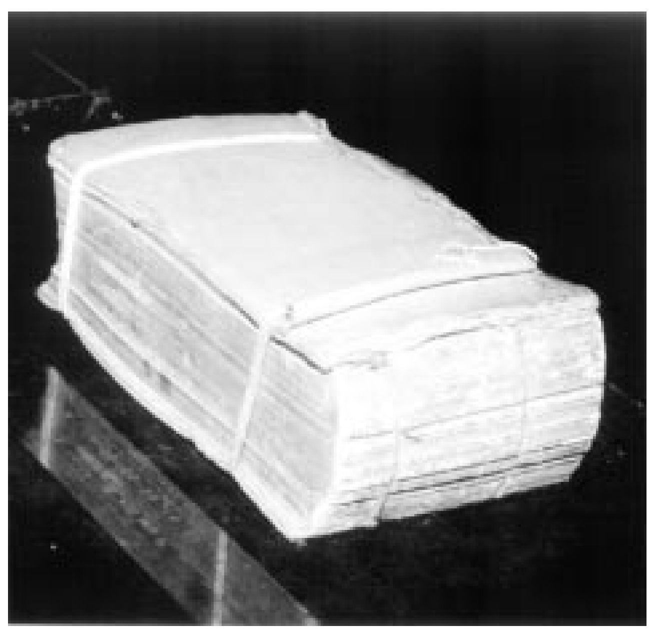


Fig. 10. One of Bose's polarizers was a cutoff metal-plate grating, consisting of a book (Bradshaw's *Railway Timetable*) with sheets of tinfoil interleaved within the pages.

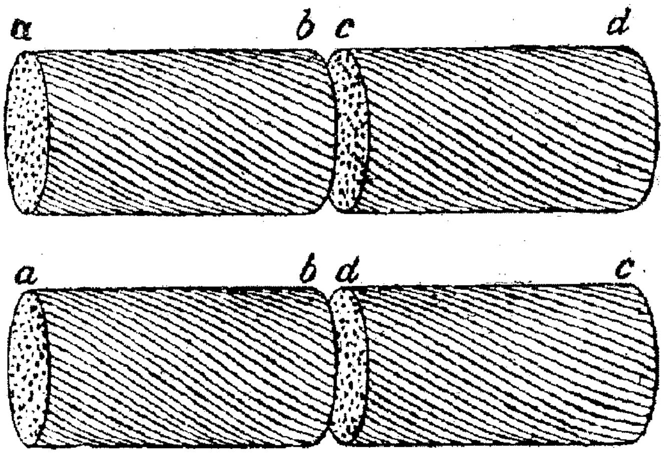


Fig. 11. Bose's diagram of twisted-jute polarization elements used to macroscopically simulate the polarization effect of certain sugar solutions (Photograph from [8]).

Fig. 12. One of the twisted-jute polarizers used by Bose.

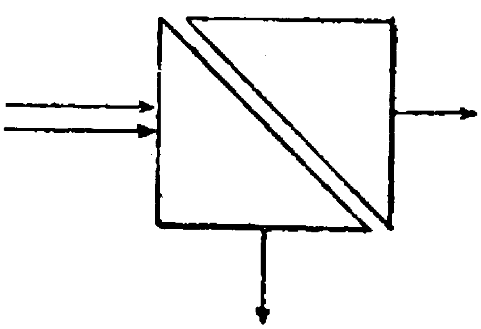


Fig. 13. Bose's 1897 diagram of the double-prism attenuator (Photograph from [8]).

of the 19th century. At about the end of the 19th century, many of the workers in this area simply became interested in other topics. Attention of the wireless experimenters of the time became focused on much longer wavelengths, which

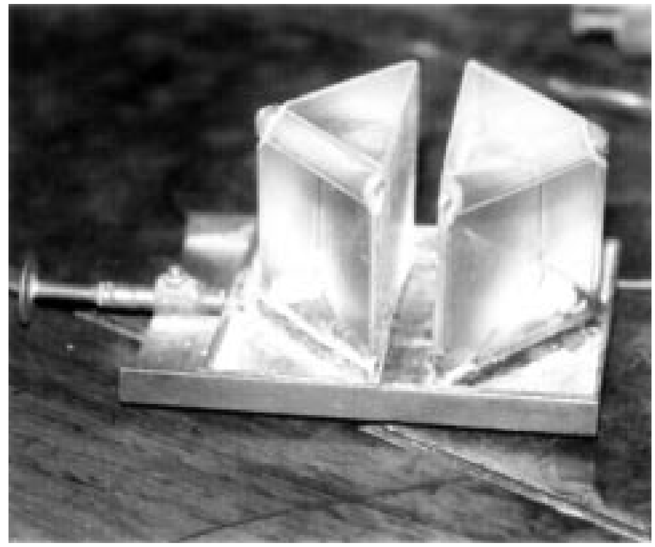


Fig. 14. One of Bose's original double-prism attenuators with adjustable air gap.

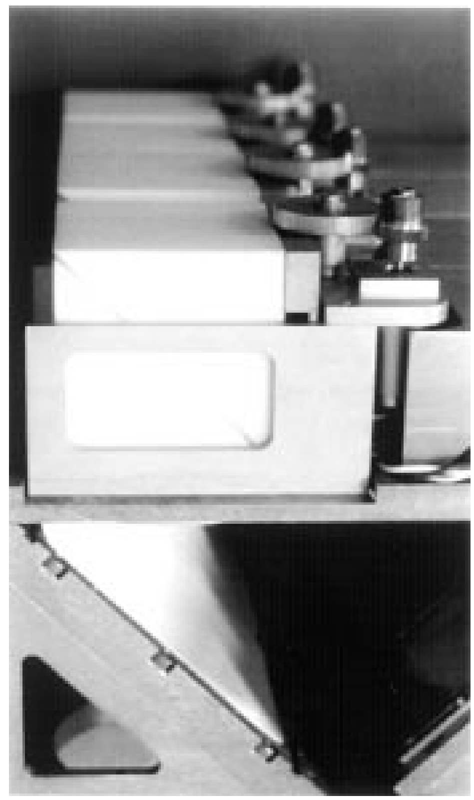


Fig. 15. Four of the eight double-prism attenuators used to control local-oscillator injection into the NRAO 1.3-mm eight-beam receiver in use on the 12-m telescope at Kitt Peak.

eventually, with the help of the then unknown ionosphere, were able to support signaling at very much greater distances.

Although it appears that Bose's demonstration of remote wireless signaling has priority over Marconi, that he was the first to use a semiconductor junction to detect radio waves and invent various now commonplace microwave components, outside of India, he is rarely given the deserved recognition. Further work at millimeter wavelengths was almost nonexistent for nearly 50 years. Bose was at least this much ahead of his time.

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