Introduction to “Some Fundamental Experiments with Wave Guides”

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Invited Paper

The early history of waveguides is reviewed. This is followed by a brief review of the events that led Southworth to undertake an investigation of waveguides, along with some of the difficulties that he encountered. The rediscovery of the hollow tube waveguide by Southworth, and independently by Barrow, and perhaps also by Brillouin, is described. The paper concludes with a brief summary of the awards and professional recognition Southworth received for his many accomplishments.

Keywords*—*Electromagnetic waves, Southworth, waveguides.

I. Introduction

For those of us who entered the microwave field following the end of World War II, the name of George C. Southworth (Fig. 1) was well known. He was widely recognized as the individual who moved waveguides from a forgotten scientific curiosity to a transmission medium and essential component that launched the ensuing microwave technological explosion during the war years and the period thereafter. The events that led up to Southworth’s pursuit of the properties of waveguides is a fascinating story of how one man’s curiosity in the formative years of this new high-frequency frontier led to a new technology that would have a profound impact on the development of radar and microwave communications. The story has been told by Southworth himself [1], [2], as well as in papers by Packard [3] and Oliner [4]. In this introduction to Southworth’s Classic Paper “Some Fundamental Experiments with Wave Guides,” we have freely drawn from these sources of information.

Southworth was born in the rural community of Little Cooley, PA, on August 24, 1890. He attended the local high school, and like so many prominent engineers and scientists of his generation, he had developed a keen interest in radio by the time he was a senior. This interest in radio stayed with him throughout his professional life. After graduation

Fig. 1. Photograph of George Clark Southworth (1890–1972). (Reprinted from *Trans. IRE, Microwave Theory Tech.,* vol. MTT-3, Jan. 1955.)

from high school he taught grade school for two years before enrolling at Grove City College. He graduated from Grove City College in 1914 with a major in physics. He continued with graduate studies at Grove City College and further pursued his interest in radio physics.

In 1916 he enrolled as a graduate student at Columbia University but left a year later to take a position in the Radio Section of the National Bureau of Standards in order to participate in the war effort. In 1918 he moved again, this time to Yale University to train Signal Corps officers until the war ended. He remained at Yale teaching first-year physics and assisting in a graduate laboratory where

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Fig. 2. Maxwell in 1855 as a student at Cambridge. He is holding the color wheel he devised for experiments in color vision, work for which he was awarded the Rumford Medal of the Royal Society in 1860. (Reprinted from *Engineers and Electrons: A Century of Electrical Progress.* New York: IEEE Press, 1984.)

his knowledge of radio was in great demand. He liked his teaching duties but realized that to succeed as a faculty member he would need to obtain the doctorate degree. Thus he enrolled as a graduate student again in 1920 and earned the Ph.D. degree from Yale in 1923. His dissertation topic was the measurement of the dielectric constant of water at radio frequencies (15 MHz). This was accomplished by measuring the wavelength of electromagnetic waves on a Lecher wire frame (two conductor transmission lines) located in air and immersed in a trough of water. It was during this investigation that he discovered some spurious waves whose existence were a mystery. These waves could be excited even with the Lecher wire frame removed from the trough of water. Southworth had heard that Shriever in Germany had explored waves on dielectric cylinders and believed that this might be related to his observations. The opportunity to pursue the investigation further at this time was not available, but he did observe that by reducing the size of his apparatus the mysterious spurious waves disappeared. As we will discuss later, the lingering curiosity as to the nature of these spurious waves triggered his investigation into waveguides some eight or nine years later.

II. The Early History of Waveguides

In 1865, Maxwell (Fig. 2) published his theory of electromagnetic waves. By 1890, Hertz (Fig. 3) had convincingly demonstrated the existence of electromagnetic waves and their similarity to light and thus verified Maxwell's theory. From this point on, various theoretical and experimental investigations were carried out by many people that led to a rapid development of wireless radio communications. The theoretical physicists were well equipped to explore electromagnetic waves because of their expertise with acoustic and mechanical waves and vibrations and associated mathematical tools. The experimental physicist was not as fortunate

Fig. 3. Heinrich Rudolf Hertz. (Reprinted from *Engineers and Electrons: A Century of Electrical Progress.* New York: IEEE Press, 1984.)

since the only readily available source of electromagnetic radiation was the spark gap with its broad spectral output. Nevertheless, by clever use of specially designed spark gaps, resonant dipoles, and resonant circuits, they were able to conduct meaningful experiments.

Jagadish C. Bose (Fig. 4), a renowned physicist and professor at the Presidency College of Calcutta, conducted a variety of experiments with millimeter waves during the period 1894–1900. He designed a special resonant spark gap and transmitted the electromagnetic energy through a rectangular waveguide, from which it was radiated outward from the open far end [5]. The apparatus was a key component in a spectrometer that he constructed for his experiments. This appears to be the first systematic experimental use of a hollow pipe waveguide to propagate electromagnetic waves. His mentor, Lord Rayleigh (Fig. 5), returned to England after visiting Professor Bose's laboratory and in the following year published a remarkably complete theory of electromagnetic waves in circular and rectangular waveguides. It included the recognition of two wave types that we now refer to as E or transverse magnetic (TM), and H or transverse electric (TE) modes, along with their cutoff wavelengths [6]. The work of Lord Rayleigh established the need for a hollow tube to have a cross-sectional dimension on the order of a wavelength in order to support a propagating electromagnetic wave.

A few years later, Weber gave a physical interpretation of why the phase velocity was greater than the velocity of light in the unbounded dielectric medium [7]. The explanation was based on the zig-zag path followed by the wave as it bounced back and forth between the waveguide walls as

Fig. 4. Jagadish Chandra Bose—the scientist.

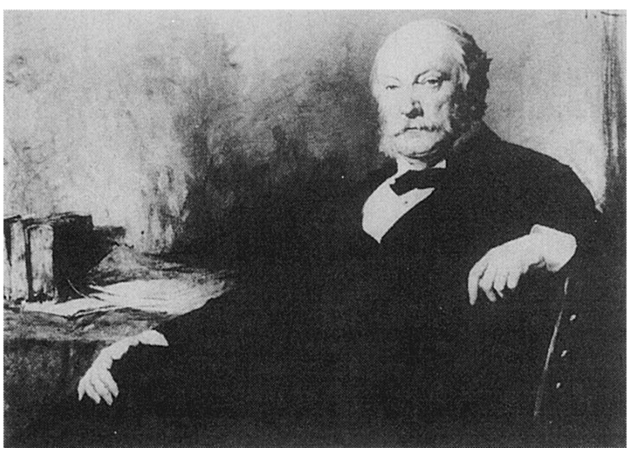

Fig. 5. Lord Rayleigh, Cavendish Professor of Physics (1879–1885) succeeding Maxwell at Cambridge University, Cambridge, U.K. He was the first British scientist to receive the Nobel Prize for Physics (in 1904) for the discovery of the gas argon. He taught physics to Bose and patronized Bose's pioneering research with millimeter waves in the Victorian British empire.

it propagated through the waveguide. Further work on the hollow metal tube waveguide was published by Silberstein, who examined the dispersion properties of waveguides [8].

From 1915 to the early 1930's, work on the hollow metal tube waveguide went into a dormant state, most likely because of the concentration of research and development on the rapidly expanding field of radio communications at low frequencies, where waveguides did not have a role. However, before moving on to what occurred in the 1930's, we need to point out a number of related studies of guided waves on dielectric cylinders, which seem to have attracted more interest than the hollow tube waveguides in the period up to 1930.

As early as 1899, Sommerfeld investigated the propagation of a circular symmetric mode on a single thin conducting wire [9]. Harms extended the analysis to a dielectric coated wire in 1907 [10]. Sommerfeld's work was also extended by Hondros to include noncircular symmetric modes in 1909 [11]. The propagation of waves along dielectric cylinders appears to have been initiated by Hondros and Debye, who found the mode solutions for this structure in 1910 [12]. Some years later, Zahn became interested in waves on dielectric cylinders [13] and later assigned a study of this problem to his student Shriever [14]. Shriever carried out an experimental investigation and used a continuous wave oscillator instead of a spark gap in his experimental work. All of the above work was carried out in Germany and published in German and so was not as widely known as it should have been by researchers in the United States.

A number of guided modes can exist on dielectric cylinders. These are generally hybrid modes (i.e., a combination of E and H modes) and exhibit a low-frequency cutoff, with the exception of the HE_{11} mode, which can exist all the way down to zero frequency. The circular symmetric modes are pure E and H modes. The dispersion properties of the modes on a dielectric cylinder are quite similar to those of modes in a hollow metal tube. That this is so can be surmised from an examination of Figs. 9 and 10 in Southworth's Classic Paper. From an experimental point of view, the modes might be considered to be much the same unless the theoretical description of the modes was available so that the differences could be understood. There is a significant difference, which is that the phase velocity of the modes on a dielectric cylinder is always less than that of lightwaves in the unbounded dielectric medium, while for cylinders enclosed in a metal tube the phase velocity is always greater than that for lightwaves in the unbounded dielectric medium. For dielectric cylinders, the phase velocity becomes equal to that of light in free space at the cutoff frequency, while for metal tube waveguides the phase velocity becomes infinite at the cutoff frequency.

III. The Rediscovery of Waveguides

After graduating from Yale, Southworth accepted a position with American Telephone and Telegraph Company in New York in 1924. He was assigned to help edit the newly formed *Bell System Technical Journal.* This task did not appeal to him, so he requested a transfer and was subsequently assigned to the Development and Research Department. For the next several years he was engaged in field measurements on shortwave radio transmission equipment. There was no research being done—in fact, members of the department were not allowed to engage in research. Southworth was still looking for an opportunity to carry out an investigation on the nature of the spurious waves he had found during his research at Yale. He had Shriever's paper on waves on dielectric cylinders translated but did not find that it really explained the phenomenon that he had observed. He decided to ask the Netcong radio station test facility to build equipment for him that was similar to that he had used at Yale. He then undertook to investigate waves on cylinders of Bakelite filled with water, as well as copper tubes filled with water. He described his work to his immediate supervisor as tests on shortwave transmission so as not to violate department policy that prohibited engaging in research. In the early stages of his investigations, Southworth seemed to not make any great distinction between the waves he was able to excite in the two structures. The waves were generally referred to as dielectric waves, a nomenclature that carried over into later patent filings.

Southworth requested the company library to provide translations of the papers by Sommerfeld, Hondros and Debye, and Zahn that had been cited in Shriever's paper. This seemingly innocuous request came to the attention of Espenschied, a higher level supervisor, and it raised suspicions as to the true nature of the work being carried out by Southworth. As a consequence, Southworth felt compelled to more fully explain his activities, which he did in a memorandum entitled "Transmission through Dielectric Cylinders." Several copies of this memorandum were sent to Espenschied in April 1932. Espenschied circulated the memorandum to a number of potentially interested parties. He expressed skepticism about the usefulness of the work but felt that Southworth should be allowed to continue the work for a short period of time before any decision for company support would be made.

Southworth's experiments at Netcong had been successful in that he had been able to excite waves in a copper tube filled with water and measure their wavelength. This success was damped by a May 1932 memorandum from John Carson, Head of the Mathematics Department, who was a recipient of Southworth's memorandum to Espenschied. Carson had carried out a preliminary analysis of Southworth's scheme and concluded that the "proposed system of transmission is not practicable." This would have terminated any further work by Southworth were it not for the fortunate circumstance that Carson reexamined his analysis, discovered he had made an error, and sent a memorandum to Southworth in June 1932 admitting his mistake and concluding that indeed it was feasible to transmit the dielectric waves proposed by Southworth. Carson went even further and asked a staff mathematician, Sallie Mead, to undertake a more complete analysis of Southworth's proposed transmission scheme. In August of that year, Mead circulated a memorandum entitled "Dielectric Cylinders: Transmission Characteristics" that gave the results of her analysis, and by December 1932 she had also completed her investigation of the waveguide problem and prepared a memorandum entitled "Dielectric Cylinders with Metallic Sheath."

Sergei Schelkunoff, a relatively new member of the Mathematics Department, undertook an independent investigation of the problem. By the middle of 1933 both Mead and Schelkunoff had completed a thorough study of the mode spectrum in waveguides, the dispersion properties, cutoff wavelengths, and attenuation. Both Mead

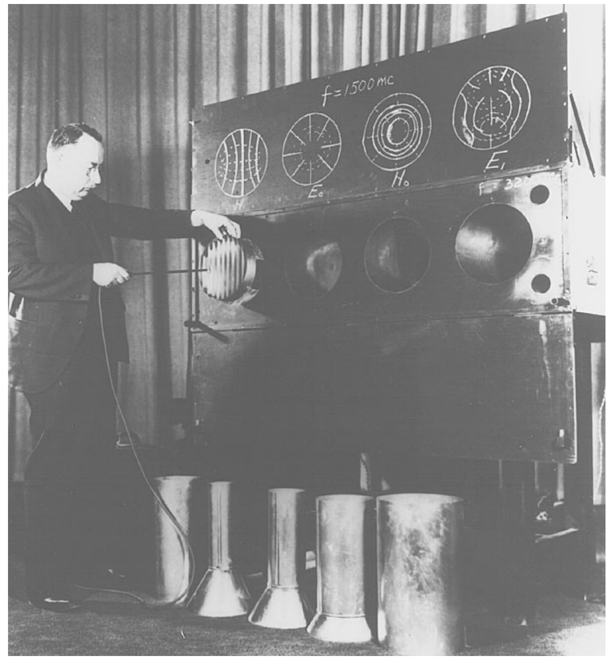

Fig. 6. George C. Southworth discusses the effects of waveguide design on electromagnetic wave propagation and transmission. His July 1937 paper was based on his practical experimentation with waveguides. (Courtesy Bell Labs/Lucent Technologies.)

and Schelkunoff independently identified the H_{10} (TE_{10}) mode as a unique mode whose attenuation decreased with increasing frequency. It was quickly realized that this mode had the potential to provide a long-distance low-loss transmission medium with a large bandwidth.

While all of the analytical work was going on, Southworth continued with his experimental investigation. He devised means to selectively excite different modes and to efficiently couple energy into and out of these modes. A number of basic waveguide devices were developed for facilitating measurements and for probing the field configuration of the different modes. In mid-1933 he was able to obtain a high-frequency triode from France which produced oscillations with a wavelength around 15 cm. This enabled him to demonstrate propagation of waves in air-filled metal tubes 4-in in diameter. In July 1933, this waveguide was demonstrated to Espenschied and Green. By now the accumulated theoretical and experimental results on the transmission properties of waveguides (Fig. 6) was of sufficient impact to launch a company project to build a long waveguide test unit. A waveguide 875-ft long was constructed and both telephone and telegraph signals were successfully transmitted through it (Fig. 7). The work had now advanced to a stage where company officials decided to transfer further work to Bell Labs and begin a substantial development program of waveguides as a means of communications. Southworth was transferred to Bell Labs, Holmdel, NJ, to work on the project.

For any profit-oriented industrial company, patent protection is taken seriously. Southworth sent several patent disclosures to the Patent Office describing his apparatus and work on dielectric waves. The early work, although

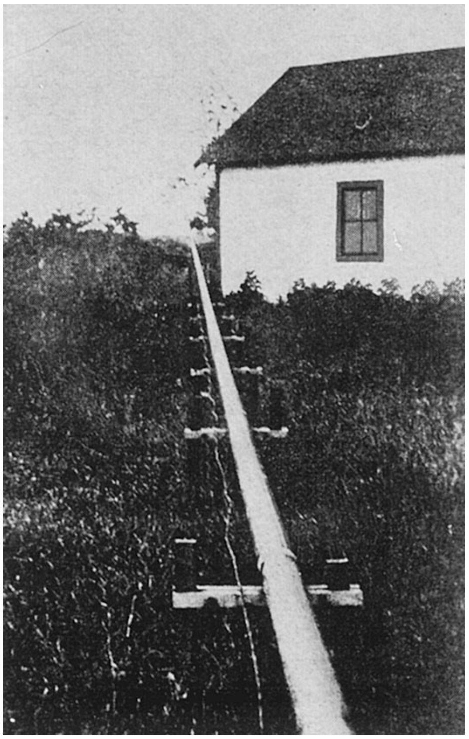

Fig. 7. A section of the first waveguide transmission line built in August 1933.

both water-filled Bakelite and copper tubes were used, was conceptually focused on waves on dielectric cylinders. The change in focus came about when the analytical results on the mode spectrum of the metal tube waveguide had been fully understood and was of such impact that it led Carson to assert that it was he and Mead that had invented the hollow tube waveguide. The use of dielectric cylinders within the metal tube was now understood to be nonessential.

It is curious that during this two-and-a-half years of activity by several people, no one uncovered the 1897 paper by Lord Rayleigh, or the more recent paper by Silberstein published in 1915, only some 16 or 17 years prior to the commencement of Southworth's work. Both of these papers appeared in well-known scientific journals and were published in English. Lord Rayleigh's paper was not discovered by Southworth or any of the professional mathematicians working on the problem. It was brought to the attention of Southworth by Harvey Curtis, an engineer working for Southworth on the design of a coaxial line to circular waveguide transformer. This information was transmitted to the Patent Office for its obvious possible impact on any patent application. Of course, the discovery of this paper made Carson's claims untenable. The internal disputes about patent issues were resolved by the fall of 1933, generally in favor of Southworth, who had the original ideas and "reduction to practice." One cannot help but speculate that if Bose's work had been better known, might he not have been credited with the first reduction to practice for waveguides?

With the patent issues resolved, Southworth sought permission to publish a paper on his findings. However, the company officials decided that it was premature to publish a paper because the new technology was still relatively undeveloped and its future uncertain. It was not until the middle of 1935 that permission was granted and a paper was prepared for publication in the April issue of the *Bell System Technical Journal.* In addition, an oral presentation was scheduled for an April 30, 1936 joint meeting of the American Physical Society and the Institute of Radio Engineers in Washington, DC.

In March of 1936 Arthur Samuel, a coworker at Bell Labs, returned from a visit to Massachusetts Institute of Technology (MIT) and informed the group at Bell Labs that waveguide work was also being carried out at MIT. This must have come as a big surprise to Southworth and was confirmed shortly thereafter when he received the program announcement for the upcoming joint URSI/IRE meeting in Washington, DC. It listed a paper, "Transmission of Electromagnetic Waves in Hollow Tubes," to be presented by W. L. Barrow of MIT on May 1, 1936, just one day after Southworth's scheduled presentation. Southworth then entered into correspondence with Barrow, exchanged papers, and between them they resolved any potentially embarrassing situations that could have occurred from lack of awareness of each other's work.

Barrow's work had begun in 1932, and he had directed his attention to the design of electromagnetic horn antennas that would produce a narrow beam of radiation to be used for aircraft navigation. During this work he conceived of the idea of using a metal tube to feed electromagnetic energy to his horn antenna. His first attempt failed because he used a metal tube that was too small to support a propagating electromagnetic wave at the frequency with which he was working.

Barrow had obtained the M.S. degree from MIT in 1929 and then gone to the Technish Hochschule, Munich, Germany, for further studies. He studied electrodynamics under Sommerfeld and applications of Maxwell's equations under Schumann. His dissertation work was in acoustics. With his background in acoustics, Barrow may have originally thought that a principal electromagnetic mode could be propagated in a metal tube independent of the size of that tube.

Since his tests on the transmission of electromagnetic waves through a hollow tube had proven to be negative, Barrow undertook an investigation of electromagnetic waves in hollow tubes. By the summer of 1935, he had developed the theory of electromagnetic wave propagation in hollow metal tubes. Barrow was also apparently unaware of the early work by Lord Rayleigh and the later work by Silberstein. It would appear that neither of his two mentors, Sommerfeld and Schumann, had considered metal tube waveguides to be sufficiently important topics to include in their lectures. Thus the hollow tube metal waveguide was rediscovered a second time by Barrow.

The papers by Southworth and Barrow were presented as scheduled. In addition, several more papers on waveguides were published in 1936 and 1937 by various people who had worked on the problem, including the Classic Paper by

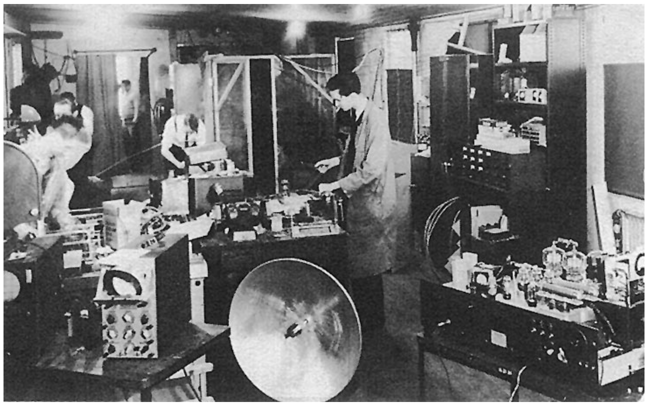

Fig. 8. The roof laboratory main room at the MIT Radiation Laboratory. (Reprinted from *Engineers and Electrons: A Century of Electrical Progress.* New York: IEEE Press, 1984.)

Southworth, republished in this issue [15]–[18]. It should be noted that another well-known scientist, Leon Brillouin, published a paper entitled "Propagation of Electromagnetic Waves in a Tube" in 1936 [19]. Was this a third rediscovery of the waveguide?

IV. THE FINAL OUTCOME

With hindsight we can see that the work of Southworth and Barrow most likely was instrumental in producing the events that followed shortly after the United States entered World War II. The National Research Committee established the Radar School and Radiation Laboratory at MIT, and Barrow was the Director of the Radar School. Bell Labs, through its parent company, Western Electric, became a major contractor for radar development and the manufacture of radar systems. Without the base of technology that had been developed at Bell Labs and MIT (Fig. 8), it is an open question whether these events would have occurred. The work of Southworth was certainly an important contribution to the rapid early development of radar and microwave systems that took place during the war years. The basic principles and techniques of waveguide technology had already been established by this early work and was ready for refinement and a broader range of applications. After the war ended, Bell Labs entered into a substantial development effort to perfect the low-loss waveguides, based on the attenuation characteristics of the H_{10} mode that had been identified earlier by Mead and Schelkunoff. However, these waveguides were not put into commercial use since they were replaced by lasers and low-loss optical fibers as a preferred medium for long-distance broadband transmission.

V. THE LEGACY OF GEORGE CLARK SOUTHWORTH

Southworth was best known for his waveguide work, in part from the publication of his text *Principles and Applications of Waveguide Transmission* that appeared in 1950. However, his professional work encompassed a number of diverse areas related to antennas, microwave communication systems, and radio astronomy. He was the first to detect microwave radiation from the sun [20]. He received many honors and awards during his professional career. For his work on waveguides he received the 1938 Morris Liebmann Prize of the Institute of Radio Engineers, and in 1947 the Stuart Ballantine Medal from the Franklin Institute. For his work on microwave radiation from the sun he received the Louis Levy Medal of the Franklin Institute in 1946. He was elected a Fellow of the Institute of Radio Engineers in 1942 and was also a Fellow of the American Physical Society. In 1963 he was awarded the IEEE Medal of Honor "for pioneering contributions to microwave radio physics, to radio astronomy, and to waveguide transmission." He was a founding member of the IEEE Microwave Theory and Techniques Society and later was made an Honorary Life Member of the Society. He passed away in 1972 at the age of 82.

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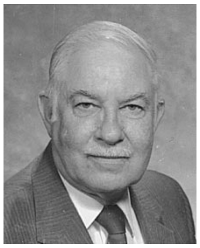

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Dr. Collin received the Antennas and Propagation Society Distinguished Career Award and the Schelkunoff Prize Paper Award in 1992. He is a member of the National Academy of Engineering and several other professional societies.