Coaxial Transmission Lines, Related Two-Conductor Transmission Lines, Connectors, and Components: A U.S. Historical Perspective

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I. Pre-World War II

A. Early Years: Development of the Theory of Guided Electromagnetic Waves and Validation by Experiment (1880–1900)

THIS SPECIAL ISSUE of the TRANSACTIONS ON MICROWAVE THEORY AND TECHNIQUES in observance of the first 100 years of the IEEE has an especially interesting parallel for the history of guided electromagnetic (EM) waves. It was in this decade 100 years ago that Heinrich Hertz, a German professor of physics, carried out his original experiments which demonstrated the reality of the Faraday-Maxwell theory of the wave nature of light and electricity and the central thesis that they are essentially the same. According to Hertz, "the result of the experiments is to confirm the fundamental hypotheses of the theory" [1, p. 20]. He acknowledged the problems of following Maxwell's difficult style, with its "unwonted mathematical difficulties," and of not always being quite certain of having grasped the physical significance of Maxwell's statements.

It may not be generally realized that most of Hertz's experimental work concerned guided electromagnetic waves. His experiments on waves in free space are those most often referred to in the literature.

In addition to being a gifted and resourceful experimenter, Hertz had a complete grasp of the mathematics and the theory of his work. He was quite capable of contributing on his own, which he did [1, ch. 9]. He had the benefit of then-current work by others which helped render Maxwell's work more tractable and amenable to investigation and experimental demonstration. If there is one person who stands out, it is the reclusive genius Oliver Heaviside [illegible]. Convinced of the validity of Maxwell's theory, Heaviside wrote a series of 47 papers between 1885 to 1887, all under the title of "Electromagnetic Induction and its Propagation," progressively laying the mathematical foundation for understanding guided electromagnetic waves, and for modern transmission-line theory.

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It is interesting to follow the progress of Hertz's investigations in a series of papers from 1887 to 1891. These were published in a book with a foreword by Hertz. The book was translated into English soon thereafter [1]. Hertz developed experimental techniques [1, ch. 2] making use of a spark discharge oscillator at a frequency of about 60 MHz. Hertz had searched for seven years (1879–1886) to discover how to design a suitable high-frequency signal generator [1, p. 1]. A contribution of his was the resonant circuit (referred to as the primary). For 60 MHz (5 m of wavelength), he used a loaded half-wave dipole. The dipole, in its now familiar configuration, had a gap in the center. The two halves were charged to a high potential difference by an induction coil and battery until breakdown occurred across the gap. The resulting spark formed a conducting path, and the dipole configuration as a whole fell into damped oscillation, converting stored energy to energy radiated at a frequency corresponding to the resonant frequency of the dipole. With a detector and indicator (referred to as the secondary) consisting of a micrometer-adjustable spark gap in a variable-length loop of wire, he was able to show resonance effects by tuning either the oscillator or the detector [1, p. 44]. Using the same apparatus, Hertz conducted experiments to demonstrate the existence of Maxwell's displacement current [1, ch. 6].

Hertz proceeded to show that waves propagated on wires have a finite velocity [1, ch. 7]. He investigated waves in air, and observed standing waves caused by interference between direct waves and waves reflected from metallic surfaces, the position of such a surface corresponding to the position of a minimum [1, ch. 8]. He could have stopped there and might easily have claimed to have achieved his goal, but he did not.

Hertz went on to conduct experiments with shielding and with coaxial-line configurations [1, ch. 10]. Maxwell [3, p. 385] had explicitly suggested the phenomenon of "skin effect" [4], the tendency of high-frequency alternating currents and magnetic flux to penetrate into the surface of a conductor only to a limited depth. Hertz conducted experiments by completely enclosing his detector in a box of thin metallic sheets of various materials. No signal was detected even for wall thicknesses estimated to be no more than 1/20 mm. When Hertz used the same sheet material to form the outer conductor of a coaxial line, similar shielding was obtained. To get an even thinner outer conductor, he then took glass tubes which had been chemically silvered and used them as the outer conductor. Sparks only appeared in his external detector "when the film of silver was so thin that it was no longer quite opaque to light, and certainly was thinner than 1/1000 mm" [1, p. 166].

Hertz next described experiments in which he used a coaxial-line section consisting of a central wire through the axis of a wire-cage cylindrical tube 5 m long and 30 cm in diameter [1, p. 169]. His detector was again a resonant loop of wire containing a variable-length spark gap. This time the loop was made smaller, with copper wire 1 mm thick coiled tightly into a spiral of 1 cm diameter with about 125 turns, pulled out a little, and bent into a circle of 12 cm diameter. An adjustable spark gap was inserted between the free ends. This detector was small enough to fit inside the coaxial line. With it Hertz demonstrated standing waves, with nodes a half wavelength from a short circuit and a quarter wavelength from an open circuit; and he showed that the wavelength inside the line was the same as for a corresponding wave in free space (with the same dielectric; in this case air).

In order to study focused radiation in space [1, ch. 11], Hertz constructed a cylindrical parabolic reflector 2 m high, 1.2 m wide, 0.7 m deep, and 12.5 cm focal length. He also built a new oscillator which operated at a much higher frequency of about 450 MHz (67-cm wavelength). For this wavelength, the resonator was now a simple dipole of 3-cm-diameter brass tubing and 26-cm overall length. The dipole was mounted along the focal line of the reflector and connected to the discharge spark gap behind the reflector through a short length of two-wire transmission line. A focused beam was obtained (undoubtedly a very wide beam), and Hertz has described effects akin to optics: rectilinear propagation, polarization, reflection, and refraction [1, pp. 176–185].

Thus, Maxwell's theory had been validated in detail by Hertz. At this point, knowledge was available for the development and use of guided electromagnetic waves. However, practical use of the knowledge awaited the advent of commercial need and new technology. Of the latter, signal sources and materials are two notable examples.

Hertz was the first microwave engineer, and the only one for over a generation. Although the highest frequency used in his experiments, 450 MHz, is at the lower bound of what we would consider to be the microwave frequency spectrum, Hertz's techniques were only improved upon in detail and not in principle when the need for radar developed in the mid-1930's, leading to a new profession: microwave engineering.

As an aside, Hertz probably never heard of hollow waveguide as a transmission line for EM waves. He died in 1894, after publication of his book, *Principles of Mechanics*. In 1893 [5, p. 400], Heaviside raised the question "whether we cannot transmit an electromagnetic wave along the interior of a tube, in a manner resembling a beam of light?" He did not conceive of how it could occur: "It does not seem possible to do without the inner conductor, for when it is taken away we have nothing left upon which the tubes of displacement can terminate internally, and along which they can run."

It was Rayleigh [6] who, in 1897, showed mathematically that waves could indeed propagate in a space bounded by a conducting tube. He did this by solving the boundary value problem for Maxwell's equations in a space surrounded by a cylindrical conductor. Rayleigh did this also for a rectangular cross section. His analysis showed that such waves could exist in a set of well-defined normal modes, and also that there must be a longitudinal component of field, either the electric or the magnetic, giving either TE or TM modes of propagation as we know them. Furthermore, Rayleigh showed that waves could propagate only if the frequency were above a lower limit set by the diameter of a circular pipe, or width of a rectangular pipe, and the mode number. For example, at Hertz's higher experimental frequency of 450 MHz (67-cm wavelength), the inside diameter of a circular guide would have to be at least 39 cm (0.58 wavelength), and the width of a guide of rectangular cross section at least 33.5 cm (0.5 wavelength). Hertz's 30-cm-diameter cylinder used in coaxial-line experiments would have been too small. It is safe to assume, however, that had Hertz been alive, he would easily have comprehended the theory, and would likely have carried out an experiment to validate the theory. The propagation of EM waves through metal pipes was used by investigators in Germany before the turn of the century, and scientific interest and use continued, but it was to be forty years before high frequencies (i.e., microwaves) were used commercially. This delay can largely be explained by two factors: 1) lack of suitable high-frequency sources (technology push) and 2) lack of pressing need (market pull).

In the meantime, new and developing industries were providing the foundations of applications and new technology for a future microwave industry.

B. New and Developing Industries: Electric Power and Communications

By 1890, electricity in the form of electrical power had become an important factor for industry, transportation, and lighting, with service supplied from central generating stations. The electric telegraph using wires had undergone 50 years of development with widespread use, including ocean-spanning underwater cable. The telephone, although much newer, was in an advanced stage of development and commercial use had started. The recognition of the potential of EM waves for radio, as wireless telegraphy, was soon to follow. Both the technology and the application of radio at that time favored lower frequencies.

A significant factor in the development of electromagnetic science and technology has been the availability of suitable energy sources. The spark discharge generator used by Hertz is very inefficient, with only a small fraction of the total energy at the frequency of interest. The efficiency decreases as frequency is increased. Long-distance transmission favors lower frequency, however, because of the tendency of lower frequency waves to bend around the earth. Powerful transmitters were built for lower frequencies. The broad and noisy spectrum of the spark discharge transmitter was tolerable for radio telegraphy.

The growing need for communication, both short and long distance, produced a demand for radio as wireless telephony. Vacuum tube oscillators and amplifiers were in use by 1915, starting a long progression of technology which included the telephone, carrier telephone, short-wave radio, television, and eventually radar in the 1930's.

C. Evolution and Use of Transmission Lines for Guided Electromagnetic Waves

All transmission lines in practical use until the late 1930's were of two-conductor configuration including: single-wire with implied ground plane, two-wire balanced line, and coaxial line. (All three types had been used by Hertz in his experiments.) Single-wire line is suitable for low frequencies only. Balanced two-wire line was used throughout the period and was used in radar at frequencies of 200 MHz and below throughout WW II, but its use declined after that. Coaxial line evolved in low-frequency applications because it afforded complete shielding from the severe static that is characteristic of low frequencies. Crosstalk between multiple circuits could also be eliminated by use of coaxial line.

A paper by Sterba and Feldman [7], published in 1932, on transmission lines for short-wave radio, primarily for antenna lead-in, indicates an advanced stage of engineering and testing. They compared calculated and experimental results, and discussed practical aspects of line construction such as joints and insulators. Schelkunoff's paper [8], published in 1934, gives a comprehensive view of investigations up to that time and adapts mathematical theory to engineering use. The paper by Espenscheid and Strieby [9], also published in 1934, is concerned with transmission of broad-band signals over longer distances. They described the Phoenixville, PA, installation, including coaxial line and its transmission properties, the wide-band repeater, and the terminal apparatus. Coaxial-line sizes ranging from 0.5 in (12.7 mm) to 2.5 in (63.5 mm) had been experimentally investigated to satisfy a developing need for wider frequency ranges for telephone and telegraph transmission. The possibilities of television had come into active consideration.

The relatively low attenuation of air–dielectric coaxial line led to the development of bead supports [10], [11], [12] which could be spaced along the line to support the center conductor inside the cylindrical metal tube, usually of copper. The bead supports were first made of rubber, followed by porcelain, then of ceramics. Various webbed and star configurations further minimized the amount of dielectric material present, so that the total volume of space between the inner and outer conductors could be more than 99-percent air. Continuing development and use of air–dielectric coaxial line evolved with radio broadcast transmitters to 20 MHz, then UHF radar, and later with both S-band (10 cm) and X-band (3 cm) microwave radar during WW II. The transmission line described above is generally referred to as rigid coaxial transmission line or *rigid coax*—even though it can be formed in rather large-radius bends to accommodate layout—in contrast to *flexible coax*, which is intended to withstand flexing. Rigid coax was used in the transmission line between transmitter and antenna, as well as for interconnections within equipment. The same line construction was also used to make components including filters, resonators, directional couplers, attenuators, detectors, and mixers.

Practical use of the hollow waveguide, single-conductor-type of transmission line, generally referred to as *waveguide*, awaited the availability of signal sources of requisite higher frequencies. Klystron oscillator tubes and high-power pulsed magnetron oscillator tubes fulfilled the need for signal sources in microwave radar. The inherent high-power handling capacity of waveguide was of vital importance for transmission lines carrying high power, such as the interconnection of transmitter and antenna, although such applications were a small portion of transmission-line use. Around 1940, the generation of microwave energy was still expensive, receiver noise-figure values were high, and there were no low-noise microwave amplifiers. The low attenuation of waveguide was thus attractive at that time. The physical simplicity and ruggedness of waveguide made it appealing so long as size, weight, or bandwidth were not of dominant importance. Waveguide transmission-line construction and properties made it suitable for use in components and in test equipment. Since no dielectric material is required, the use of waveguide did not depend on the availability of improved dielectric materials. Waveguide received the major share of scientific and engineering design and development effort, and most use compared to coax during WW II. This trend was not to be reversed until after 1945, when system needs turned toward greater bandwidth plus smaller size and weight, and when technological development and innovation backed up these needs.

D. Radar

The year 1937 has notable significance, since late in that year the Navy approached AT&T for a possible contract to expand the scope of work on radar [13]. A group at the Naval Research Laboratory under R. M. Page had been working on pulsed radar for several years and had pushed the use of pulsed vacuum tube oscillators to over 200 MHz and demonstrated radar detection of ships and planes [14].

The radar project at Bell Laboratories was set up at the Whippany, NJ, site in 1938 [13, p. 24]. It led ultimately to the major projects carried out by Bell Laboratories and Western Electric during WW II. More than half of all radars used by the U.S. forces in WW II were designed by Bell Laboratories and produced by Western Electric [13, p. 19].

In 1938, the work at Whippany was on radio broadcast transmitters, using frequencies up to 20 MHz. The first radar transmitters there were tunable from 500 to 700 MHz, using pulsed triodes to produce 2-kW peak power.

P. H. Smith [15] has told of the transition from 20 MHz to the higher frequencies making use of transmission-line technology from radio broadcast transmitters with attention being given to spacing of bead supports of the center conductor to minimize reflection, and to alternate designs of supports including dielectric stubs. C. A. Warren [16] recounted that when 700 MHz was chosen as the operating frequency, the change in frequency from that being used in prototype work was great enough that the transmission line and antenna showed a mismatch, requiring a respacing of the beads. Rotary joints were developed to accommodate the continuously rotating antenna. Both the transmission line and the connectors were designed by Bell Laboratories and manufactured by Western Electric.

The first high-power cavity magnetron constructed in this country was made at Bell Laboratories in November, 1940, a month after the testing there of the *S*-band (10 cm) magnetron brought over by the British mission led by Henry Tizard [13, p. 114]. The magnetron was scaled to operate at 700 MHz. C. A. Warren [16] had told of the replacement of the existing triode vacuum tube transmitter with a magnetron transmitter, giving a many-fold increase in power. The high-power magnetron transmitter tube along with the klystron tube (invented several years earlier and used as the local oscillator) immediately opened up the microwave frequency spectrum to radar. A breadboard model of an *S*-band (10 cm) radar was tested by Bell Laboratories in December, 1940 [13, p. 92]. The transmission line, rotary joint, and antenna feed were of coaxial-line construction, as told by C. C. Cutler [17]. Thus, the immense capabilities of this industrial organization were brought to bear on designing and producing urgently needed complex equipment in a short period of time. Along with this came other major contributions to the fast-developing technology on which radar was based.

October, 1940, is significant in being the date of formation of the Radiation Laboratory of the Massachusetts Institute of Technology under contract from the National Defense Research Committee (NDRC). The laboratory drew on the rich resources of the industrial, academic, and governmental laboratories and facilities of the United States and its allies to make further major contributions to the theory of the microwave art, and to application in a very wide range of operating equipment.

II. World War II

Radar dominated the work done in the microwave field during WW II, and radar system needs posed urgent requirements for operating equipment. The systems were characterized as being single frequency, so that there was essentially no requirement for broad-band components. The operating frequencies were confined to a number of narrow frequency bands throughout the microwave frequency spectrum. Thus, components could be and usually were optimized for operation around a certain frequency.

An important objective was to devise equipment which would operate at higher frequencies. The need for higher frequency operation derived from the fact that, for a given size of antenna, the beamwidth decreases with increasing frequency while gain increases. Narrow beams are required for obtaining accurate angular measurements, while increased gain is advantageous in that it gives increased detection or range if other factors—transmitter power and receiver sensitivity—are kept the same.

A move to higher frequency also leads to a smaller volume of equipment for a given system function, and this factor was sometimes important—especially for airborne applications. The choice of coaxial-line components rather than waveguide at the lower microwave frequencies was at times governed by the need to conserve space and weight, but there is little evidence of any attempt at miniaturization *per se* during this period.

Unlike many other components for radar, such as magnetrons, detector crystals, fast timing circuits, and literally hundreds of components which simply did not exist in 1940, flexible cable and connectors were being produced for radio and other low-frequency uses. A drastic increase in needs for flexible cable occurred so far as quantity is concerned, and in some cases entirely new facilities were built to meet the needs. Likewise, it was sometimes necessary to develop new components and devices. All such procurements, allocations, setting of priorities, and contracting was managed by a group in the Electronics Division of the Navy Bureau of Ships in Washington, DC, under T. M. Odarenko, who was on leave from Bell Laboratories [18]. The group figured very heavily in coordinating the design and development of cables and connectors and in the documentation and development of specifications.

The joint Army–Navy RF Cable Coordinating Committee was set up under the Bureau of Ships group for the purpose of facilitating the availability of RF cables, rigid lines, and connectors for radio and radar equipment for the Army and the Navy. The chairman of this committee was T. M. Odarenko, mentioned above. From time to time the committee published specifications on cables and connectors recommended for Army and Navy equipment. The committee consisted of about 24 individuals, representing various organizations of the military, government, and industry [19].

A. Flexible Cables

A 1946 directory [20] lists 15 companies as manufacturers of solid-dielectric flexible cables of some 40 types ranging in size from 0.116 in (3 mm) to 0.910 in (23 mm) diameter over the dielectric. Most of these companies had been brought into cable production in the early 1940's to satisfy urgent needs.

The starting point for flexible cable was dielectric insulated wire over which a basket-weave of fine wires was braided to form the outer conductor, usually referred to as "braid." Sometimes two layers of braid were used to reduce leakage. The pitch angle of the wires in the braid may be typically around 30 degrees. A protective jacket of plastic was then extruded or tubed in place.

A major advance in the 1940's was the introduction of polyethylene dielectric, largely a British development, which is electrically superior to rubber and synthetic rubber materials that had generally been used before then. The loss tangent at 0.0004 is more than ten times lower, and its dielectric constant is around 2.25 compared to 3.1 for rubber [21]. Polyethylene was allocated to defense plants on a priority basis, and several manufacturers were contracted to set up new plants to manufacture flexible cable, so urgent were the needs [18], [19]. The manufacture of polyethylene material in the U.S. was started in 1943 by DuPont, according to that company, under contract from Imperial Chemicals Industries, Ltd. Union Carbide manufactured the material under license from DuPont.

Some of the shortcomings of WW-II-era flexible cable are detailed by G. L. Ragan [22, pp. 243–273]. Abrupt discontinuities that are repeated periodically will add up to give a mismatch at the input end of a long cable at those frequencies for which the discontinuities are spaced at an integral number of half wavelengths. Flexible cables were found to exhibit bad resonances at certain frequencies, resulting from the periodic fluctuations of the diameter of the dielectric, the centering of the dielectric, or the ellipticity of the core. The braid, the key feature which gives the cable flexibility, is also a source of instability. This shows up as changing attenuation and phase during bending or thermal cycling. Assuming that the cable jacket remains tight-fitting and that the braid is tightly wound, impedance changes can still occur due to the variable contact of wires sliding on each other. Cable with a braid outer conductor has greater attenuation than that with a smooth outer conductor made from the same material. This is due to the fact that currents on conductors in a coaxial line flow in the direction of propagation. The braid wires interrupt this uniform flow, increasing the losses in the outer conductor due to extra length of current paths, in addition to losses caused by the contact resistance of the junction of braid wires.

With all that, one must wonder why someone—at least someone in the microwave field—did not try replacing the braid with thin, soft copper tubing. Ironically, tube drawing technology was not only available in the 1930's, it was used to produce "metal shielded wire" [23], as will be explained later.

B. The Type N Connector and Its Progeny

The only coaxial connector in general use in the early 1940's was the UHF connector, which is still manufactured and used in substantial quantities today. It was developed by E. C. Quackenbush of the American Phenolic Co. (later Amphenol) in Chicago [19]. The UHF connector was not deemed electrically suitable for higher frequency use, so that the connector committee undertook to develop one [24] in 1942. The type N connector was named for Paul Neill, who was on the committee and who worked in the Switching Apparatus Development Department of Bell Laboratories on West Street in New York. This is confirmed by R. A. Hecht [25], retired from Bell Laboratories, who worked in the same department with Mr. Neill and who designed several of the type N configurations. According to Mr. Hecht, the designs were RF tested at the time at very low frequencies with equipment available in the department, used in telephone work. E. A. Mroz, who was then employed at the Navy Bureau of Ships and who held responsible positions there until his retirement, related that he asked Mr. Neill one day if he would like to have a connector named after him. The answer was yes, and it was designated the type N connector [18].

To aid in the identification and the procurement of cables and connectors, a numbering system was established and commonly used. Transmission lines (cables) are described by a number such as RG-9/U (radio guide-9/universal), and connectors by a number such as UG 21/U (union guide 21/universal). Although the type N connector was not designed by microwave engineers, it did get a great deal of microwave use. Looking at the design today from a microwave point of view, it leaves much to be desired. It is not of constant impedance design. The three main (coaxial) parts, the center conductor, the dielectric, and the outer shell or body are held together by a system of steps and shoulders. These mechanical discontinuities represent electrical discontinuities and limit performance. Furthermore, the UG specifications consisted of detailed drawings of individual piece parts. Procurement could be and was made from many different sources. When brought together, the pieces would fit together. This is standardization by detailed dimensions and largely prevents electrical improvements. However, modified designs were made in an effort to improve microwave performance and still maintain interface mating capability. One of these designs [22, pp. 257–259] achieves a low VSWR at the S-band (10 cm) radar frequency and at the X-band (3 cm) radar frequency by judicious spacing of discontinuities to nearly cancel the effects of reflections at the two frequencies. At other frequencies, the performance must suffer, however, because the effects of the multiple reflections no longer cancel but add up to cause greater reflections.

The type N connector design was followed by several others, none of which appears to have received microwave design attention. The type BNC is a "baby type N" [26], somewhat scaled down in diameter and provided with a twist-lock coupling mechanism. Other connector types included the types HN, LN, and C [22], [26]. The TNC grew out of the BNC in 1956 (more later).

III. Post-World War II: 1947 to 1965

Coaxial transmission-line circuits and components came out of WW II second by far to waveguide in breadth of application and volume of sales. To allow modularizing, testing, assembling, and packaging of components into a compact system, a connect/disconnect means is required. Ideally, this connect/disconnect means would be reflectionless and transparent, have zero physical length, be rugged and stable under severe mechanical shock and vibration, and sell at a price that a systems user can afford to pay. The waveguide coupling flange comes close to meeting such an ideal. Waveguide coupling flanges of standarized size were almost universally adopted at an early date. These allow very short, almost reflectionless connect/disconnect mechanical junctions for components, transmission lines, or test apparatus. The WW II years had witnessed no technological breakthroughs in coaxial lines *per se*. This is not to downplay in any way the excellent and hard work that went into designing, developing, producing, and making use of equipment that performed well —all done on extremely tight schedules. Use of coaxial line and components was not pushed during the war years because there was relatively no need for broad-band systems; also, there had not been much push for miniaturization—reduction in size and weight. Not the least reason was that the state of the art in coaxial-line and connector technology did not present any appreciable technology push. Rigid coax with bead supports or stub supports was more narrow-band than the standardized 40-percent bandwidth of a given waveguide size. It was also more expensive than waveguide. Consequently, rigid coax *per se* ceased to be used once the equipment in which it was used was scrapped. Surviving rigid coax designs generally make use of continuous, air-articulated dielectric of TFE flourocarbon (Teflon) in some sort of a honeycomb cross section, especially for high-power applications at VHF and UHF frequencies for communications and for radio and television broadcasting installations.

The period starting in 1947 was characterized by changing systems requirements, which often included greater bandwidth and greater functional complexity, smaller size and weight and, eventually, lower power consumption. These requirements were met with major new advances in technology which sometimes came in slow, halting steps, but which nevertheless often encouraged new systems thinking. The traveling-wave tube was a dramatic development which became available around 1947, first as a broad-band (e.g., octave bandwidth) high-gain amplifier, followed by several derivatives: the backward-wave oscillator (BWO), a wide tuning range voltage-tunable oscillator; low-noise amplifiers, with lower noise figures than any amplifier or mixer to that time; and high-power, high-gain amplifiers. These microwave electron tubes of the traveling-wave tube family had a far-reaching effect on microwave systems design (technology push). In size and weight, these tubes were generally no bargain, however. Except for high-power amplifier types, both traveling-wave tubes and klystron tubes were largely replaced by solid-state devices within 30 years—generally with much reduced size, weight, voltage, and power consumption.

Microwave radio relay came into use as a supplement to coax for wide-band and long-haul communications. The broad-band and more compact systems designs, such as used in electronic countermeasures equipment, hastened a return to the use of coax and the development of new configurations of two-conductor transmission line. First, however, new test equipment was needed, and it had not been long in appearing.

The Hewlett-Packard Company entered the microwave test equipment market in a major way, with both waveguide and coax products. Several of the products, such as the octave tuning range series of signal generators, required the use of coax instead of waveguide. The Model 616A Signal Generator, 1.8 to 4.0 GHz, was brought out in 1946 [27]. It used an improved connector that would mate with the type N connector, "since the type N is more or less the industry standard" [28]. The highest frequency of use was to 12 GHz (e.g., Model 806 Coaxial Slotted Line Section). The connector design was offered to industry, but no connector manufacturer took it up to offer a complete series. Hence, there was little use of this improved type N connector design in systems [27].

A new connector design was originated in January, 1956, and quickly gained type approval: the TNC connector. Years later, J. R. Munro [29], an engineer now at Lockheed Aircraft Company, Burbank, CA, related the following history. While working at Raytheon on development of the illuminator radar for the Sparrow missile system, he had a problem of noise generated by BNC connectors under vibration. He modified the design by replacing the bayonet twist-lock coupling with a screw-thread coupling and eliminated this noise. An order was placed with a connector manufacturer, General RF Fittings, for prototype quantities. Before delivery was made on that order, a salesman came by and, to Munro's surprise, showed him a sample case which contained some connectors of the modified design. Munro said that Sandia Labs later took the connector through MIL-spec type approval rather quickly as the TNC connector. That might not have been too bad if the Air Force had not designated the TNC as the preferred microwave connector. Thus, another connector design (in addition to the type N) never intended or at least not designed for microwave applications was brought into microwave use.

New thinking in the late 1950's in two areas concerning coaxial connectors eventually helped to bring coaxial transmission-line and coax components to the forefront: precision connectors, and a performance type of specification for general-purpose connectors.

Several designs of precision coaxial connectors gained prominence: from Germany, the Precifix series made by Rhode and Schwarz; from Great Britain, the "Woods" connector by Don Woods, as well as the Marconi connector; and from the U.S., designs by General Radio Company and the National Bureau of Standards. A technical committee of the IEEE Group on Instrumentation and Measurements—usually known as the Precision Connector Committee—was formed in early 1960. The committee was instrumental in standardizing the 14-mm and the 7-mm precision connectors, usable to 8.5 GHz and 18 GHz, respectively. Company names closely associated with the final design and the production of each are General Radio for the 14-mm, and Amphenol for the 7-mm connector.

The need for a performance type of specification to replace the UG specifications, which only controlled dimensions of piece parts, was recognized in a new type of specification in the late 1950's. Dimensions were given on outline drawings, and for the interface mating dimensions only. The internal design was left to the individual manufacturer. This allowed performance improvements to be made, while maintaining compatibility with equipment in use [30]. The basic specification, MIL-C-39012, is dated February, 1964, although drafts and predecessor documents existed long before that. Individual "slash sheets," descriptive of different connector types, came later. The first was dated March, 1965. The specification eventually covered all coaxial connectors in general purpose use. Assigning credit for originating the idea of a performance specification and for the hard work, know-how, and cooperation that pulled it through is beyond the scope of this paper. Suffice it to say, the specification is a major contribution.

A. New Transmission Lines — Planar Geometry

In the early 1950's, new forms of waveguide were developed that were to make the microwave field more compatible with the general process of miniaturization that was already taking place in electronics equipment. Physically, this entailed several forms of planar transmission line, using fabrication processes related to printed circuit technology [31]. Two principal forms emerged. The first, called *stripline*, is a thin, flat conducting strip between two conducting ground planes, usually in a sandwich formed by two dielectric sheets. The second form is a conducting strip adjacent to a single ground plane and supported by a dielectric sheet in-between. The latter form became known as *microstrip* [32]. Both stripline and microstrip are two-conductor transmission lines, but they do not propagate a pure TEM mode (especially microstrip) because part of the region occupied by fields is air and part is dielectric material. An input impedance can be defined, however, and a coaxial-line connect/disconnect serves well as circuit connection.

Stripline was put to considerable systems use in the 1950's, but applications were all at the lower microwave frequencies of 12 GHz and below. The connect/disconnect means generally used was again the type N connector. Without pressure either to go to higher microwave frequencies or to miniaturize, the relatively large physical diameter of the type N was tolerated. The UG configuration of type N is rather long, however, with electrical length an appreciable fraction of a wavelength at 10 GHz. Thus, the connector becomes a considerable factor in measurements, and presents a limitation on the performance of whatever it connects.

Microstrip got a slower start in applications. The geometry was a natural for use with new, very small semiconductor packages, especially those of a beam lead type of construction. The OSM/SMA connector provided the compact, low-reflection connect/disconnect means needed for the hybrid microwave integrated circuit (MIC) of the 1960's; but that is getting ahead of the story.

B. Semi-rigid Cable, a New Use of an Old Art

The replacement of the braided outer conductor and jacket of flexible cable with a thin, soft copper tube was a small step, perhaps, but someone had to do it first. Use of this cable must be viewed as a major milestone in microwave technology, considering its wide acceptance and usage, as well as the benefits derived. Ironically, the technology for applying the metal jacket was available and used from the mid-1930's onward. The purpose of the invention, covered by U.S. Patent (Norman H. Jack, 1936) for "metal shielded wire," was to protect an insulated electrical conductor from corrosion and mechanical damage [23]. The partnership of Mainwaring and Jack, which was dissolved in 1940, and two successor companies, Uniform Tubes, Inc. and Precision Tube Company, each manufactured "metal shielded wire" [33] from that time onward.

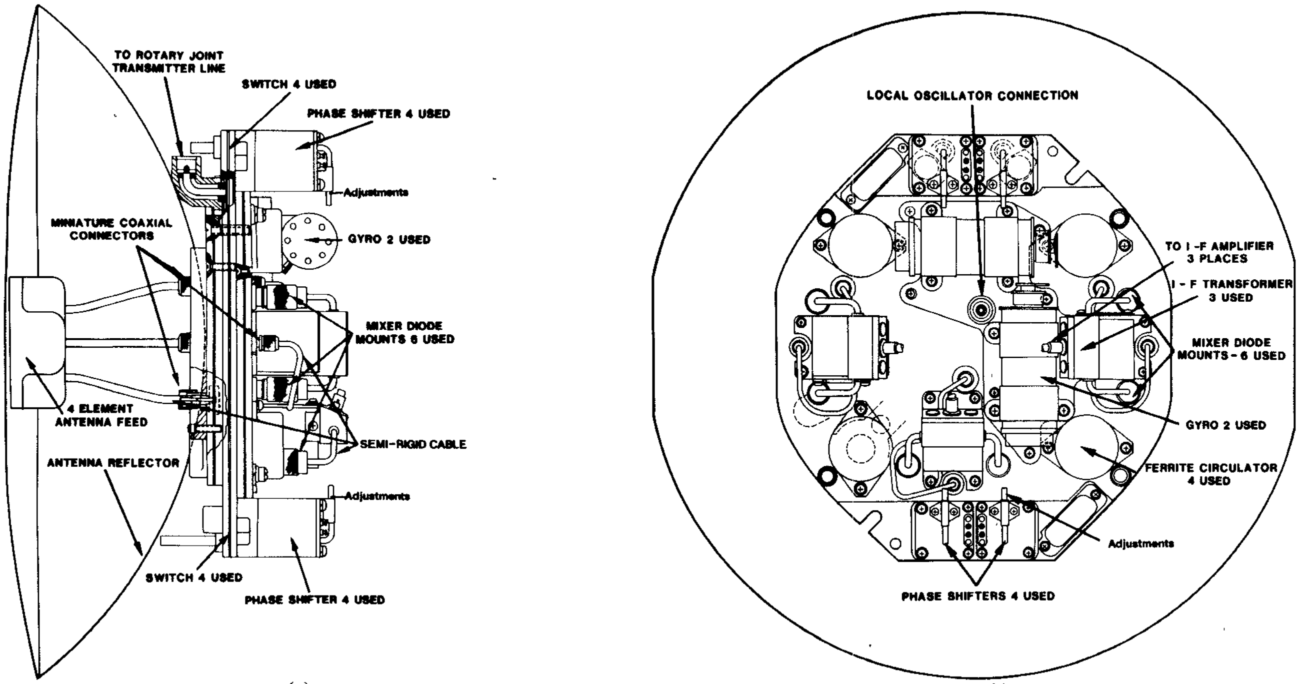
According to Matthew Balch, Jr., of Precision Tube Company, he first discussed the application of such cable for microwave use with potential customers in 1945 [34]. The advent of Teflon dielectric allowed improvement of the product because of the superior mechanical and thermal properties of Teflon compared to polyethylene. The Precision Tube Company named their product *Coaxitube*.

According to A. B. Mainwaring [33], Uniform Tubes, Inc. "became seriously interested in an engineered microwave product—in late 1961," and, in 1962, formally entered the microwave field, coining the name *Microcoax* for their cable. The state of the art in cable production had apparently advanced to the stage where the core (dielectric covered wire) could be procured that was relatively free of periodic discontinuities, with uniformity monitored by passing the core through two pairs of capacitance probes placed 90 degrees apart [33]. Omni Spectra, Inc., founded in 1962, heavily promoted the use of this cable and called it semi-rigid cable. The term caught on, and is now generally used. Compared to the corresponding type of flexible cable, the overall diameter is smaller, but other features especially set it apart. Attenuation is less, with the difference becoming greater as frequency is increased. Semi-rigid cable is stable and noise-free under conditions of shock and vibration. It gives repeatable results on thermal cycling after stabilization, which should require no more than two or three thermal cycles. To accommodate the geometry of interconnecting components and assemblies, the minimum bend radius of about 3 cable diameters is advantageous compared to about 10 cable diameters for flexible cable. Phase stability is another advantage compared to flexible cable.

Figs. 2–4 illustrate some properties of solid Teflon dielectric coax. The low dielectric constant of about 2.0 and low-loss tangent (around 0.0003) are attractive in microwave applications. An even lower dielectric constant (e.g., less than 1.5) is achieved in cable now offered by several suppliers, using partially air-filled or "expanded" dielectric with a corresponding reduction in attenuation and increase in unloaded Q (Q_0 in Fig. 4).

C. New Thinking About Microwave Circuits and Assemblies

A landmark microwave system which made use of stripline is shown in Fig. 1(a) and (b). It is the antenna and microwave assembly for an active pulse Doppler radar missile guidance seeker developed at the Bendix Research Laboratories Division under contract with the Navy Bureau



(a) (b)

Fig. 1. Artist's illustration of first microwave assembly using the miniature microwave coaxial connector and associated technology (1961). (a) Side view. The microwave circuits are contained in a three-tier stripline assembly which contains the microwave circuits for a monopulse active pulse-Doppler radar. Electronic conical scan of the antenna beam, with scan-on-received-signal only is provided. Switches are provided to select a nonscan mode of operation. (b) Rear view. The reflector is parabolic and 12 in (305 mm) in diameter.

of Aeronautics, starting in 1958. The wavelength is in *C*-band, around 5.5 cm. The antenna reflector is 12 in (305 mm) in diameter. The microwave circuits are contained in a three-tier stripline assembly of approximately 8 in (203 mm) diameter and 1 in (25 mm) thick. In addition to the usual components (such as power dividers, directional couplers, and mixers), the assembly contains four electrically variable ferrite phase shifters [35], [36], which had to be mounted outboard, four stripline hybrids, and four ferrite circulators to produce an electronic conical scan of the antenna beam, with scan-on-received signal only. Four switches are provided to remove the phase shifters from the circuit for a nonscan mode of operation. The system illustrated is the culmination of three years of engineering effort begun in 1958. It is historic in using prototypes of a new coaxial connector designed for microwave use—the forerunner of the BRM/OSM/SMA connector. It was ahead of its time as regards semiconductor packaging technology: the mixer diodes, two each for the three balanced mixers, were in ceramic packages almost 0.250 in (6 mm) diameter and 0.750 in (18 mm) long, a package design from the 1940's for use with 3-cm or longer wavelength waveguide. These diodes had to be accommodated in diode holders mounted outboard. The miniature coaxial connector was a necessity and not a choice. The low-key, logical manner in which the connector design originated is best told in the words (somewhat paraphrased) of James Cheal, the microwave engineer in charge of the group doing the work [37]:

> We soon abandoned an early waveguide design (in 1958) in favor of suspended-substrate stripline with coaxial interconnections between stacked stripline layers and the variable phase shifters which were mounted outside of the stripline assembly. It became obvious that the type N connector typically used for interconnection of cable and stripline would not be suitable due to space and weight limitations. A miniature connector was required. The microwave group was engaged in the development of components not available from other sources. Stripline circulators, electromechanical switches, and coaxial ferrite variable phase shifters were all ahead of the current state of the art. It seemed somewhat trivial by comparison to develop a microwave miniature connector. That may have been the reason why I did not assign the work to one of the microwave engineers but discussed it directly with the mechanical designer, Val Colussi, assigned to our group.
>
> The instructions to Mr. Colussi were to design a mechanical coupling for joining two 'semi-rigid' cables, to make it as short as possible and keep the diameter as small as possible consistent with standard threads and good mechanical integrity. I provided inner and outer diameter ratios corresponding to 50 ohms impedance with Teflon dielectric, and Mr. Colussi worked out the mechanical dimensions. The concept and final dimensions evolved through several discussions between us and a prototype model was built.

Thus, the type N connector had potentially met the end of the line in its dominance as the principal coaxial connector for microwave use. An elegantly simple microwave solution to the connect/disconnect problem was made available. The new connector interface featured a butt joint in the plane where the two halves of a connector join. It came to be termed BRM for Bendix Real Miniature. The interface survived through several stages of design and product development, and it became the interface design of the OSM[1] connector (1962) by Omni Spectra, Inc. Different manufacturers of compatible connector designs used

[1]OSM is a registered trademark of M/A COM Omni Spectra, Inc.

their own designations starting about 1964. SMA was adopted in 1968 as the military designation under specification MIL-C-39012.

D. Getting New Microwave Components to Market

Product possibilities represented by the components and technology in the system of Fig. 1 were intriguing. Two engineers who had been instrumental in obtaining the contract and getting the system developed—the author, John H. Bryant, and James Cheal—discussed the possibilities in detail. They realized that much remained to be done because no comparable components were on the market. A complement of components and related test equipment items to go along with them was a must. It was equally necessary to have a source of supply of the new connector in a series complete enough to allow systems to be designed and built. A potential market was believed to exist in the conventional coax microwave frequency range of 10 GHz and below—to satisfy needs not adequately filled by the technology of oversized stripline circuits and type N connectors. The technology at hand (Fig. 1) also potentially opened up the entire upper half (e.g., 10 GHz and upward) of the microwave frequency range to coax and TEM-type circuits. That was entirely visionary, however. The problem was to get a sufficient program going. Bryant and Cheal opted to go the entrepreneural route on microwave components if they could put together the support. A third colleague, V. J. McHenry, was invited to join. Other team members with backgrounds in manufacturing, and in finance and accounting, were enlisted, and Omni Spectra, Inc. was started in March, 1962. The first products were a line of miniature microwave components making use of the BRM interface. This was paralleled with some test-equipment items which had to be developed to test the components in-house.

The microwave components were individually packaged, at first, in contrast with construction in the system of Fig. 1, in which a dozen or more components might be contained on one printed circuit board. The result was the use of one or more microwave circuit connections (connectors) on each component. This gave access for testing each component and also represented the ultimate in modularity for assembly of components into packages of whatever configuration was desired [38]–[42]. Interconnection between components could at times be made directly, but was usually made through short lengths of semi-rigid cables bent to the required shape. The miniature connector proved to be excellent for this application, being short, small in diameter, and broadband with very low VSWR, but much development work remained to be done on it. Each configuration of the connector was treated as a microwave component. Minimizing length was important, and cost was a major consideration. The butt joint for the outer conductor favors short length and also facilitates repeatable results on the seating of parts. The pin and collet arrangement for the center conductor favors short length and low cost, but introduces steps that have to be compensated electrically, as do gaps that must be provided to accommodate the necessary tolerances at the mating interface. Factors such as the inductance of the longitudinal slots in the collet also have to be considered. It was found possible to compensate electrically for all of these factors and to obtain broad-band, low VSWR performance by using the principle of maintaining constant impedance throughout and compensating for any necessary discontinuity in the plane of that discontinuity. The result was a very low VSWR which slowly increases with frequency over the usable frequency range of dc to 26 GHz. An extensive study showed that tolerances commensurate with good practice in high-volume parts production (including the use of automatic screw machines) could be used. The small number of parts used helped to minimize cost. Not the least of the problems was establishing a 50-Ω transmission-line reference standard and determining the dielectric constant of Teflon. A very useful item of test equipment which had become available was the Time Domain Reflectometer (TDR).

A major challenge was to make such a small connector strong enough to withstand shock, vibration, and other environmental and user requirements, and yet give repeatable results on repeated mating and unmating. Extensive mechanical design, materials, and process studies with a view to production with standard methods and at reasonable cost resulted in a design deemed suitable for general purpose use at all frequencies.

All of the connector design work had been done to support the miniature microwave component line. The connector division of the Bendix Corporation had come to market in early 1962 with the BRM connector, but had chosen to limit the specification to 10 GHz and below. The number of different configurations was also limited.

The first major application for miniature connectors, components, and semi-rigid cable was the Navy's Typhon ship-board phased-array radar system. It was designed by the Johns Hopkins University Applied Physics Laboratory and Westinghouse, and built by Westinghouse. The frequency was in the *C*-band (around 5.5-cm wavelength). Only one model was built, but with over 2000 modules it represented a market for a substantial quantity of a few types of connectors, components, and traveling-wave tube amplifiers. Of equal importance was the fact that a major systems customer has numerous suppliers which of necessity become potential customers—a market propagation effect.

E. The OSM Connector

By September 1962, the pressure to sell connectors as well as components was building. Omni Spectra was making connectors for its own use, and had them in inventory, but in a very limited number of configurations. Omni Spectra (by then eight months old) was marketing some test instruments and accessories, including a slotted line and a reference termination, both specified for use to 18 GHz, and "usable" to 26 GHz. A complement of *X*-band (8.2–12.4 GHz) components was almost ready for market, and a complement of *Ku*-band (12.4–18 GHz) components was planned. The market looked promising, and the deci-

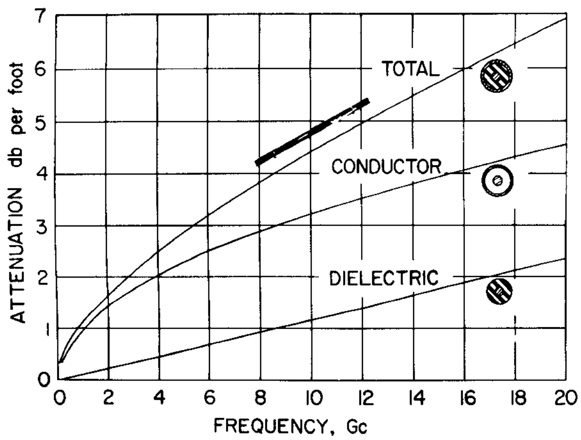


Fig. 2. Attenuation per foot versus frequency in 0.141-in O.D. coaxial line, showing contributions of conductor and dielectric losses. The outer conductor, of drawn copper, is 0.118-in inside dimension. The inner conductor, of silver-clad iron wire, is 0.050-in diameter. The dielectric is Teflon. The increasing attenuation per unit length of transmission line with increasing frequency can be misleading for applications in components or assemblies, since shorter lengths can generally be used at higher frequencies.

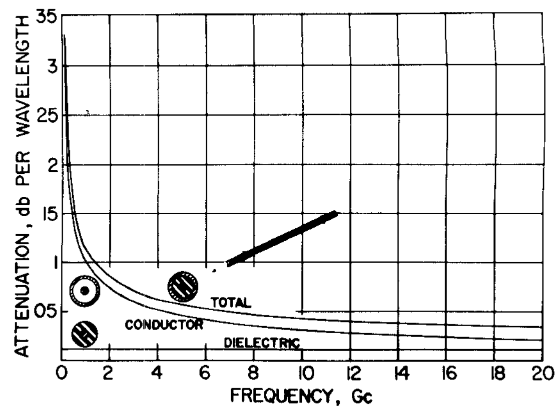


Fig. 3. Attenuation per wavelength versus frequency in 0.141-in O.D. coaxial line, showing contributions of conductor and dielectric losses. The decreasing attenuation per wavelength means that, for a given line size, the unloaded Q increases with frequency.

sion was made to advertise and sell connectors in order to promote use of the components. The time had come that a microwave company had to get into the connector business. OSM, for Omni Spectra Miniature, was adopted as the trademark. Pressure built up for more configurations, increasing the expenditure of effort, and of capital for production facilities, for MIL-spec type of qualification procedures, testing, and documentation.

Another compelling requirement for additional products and increased engineering effort came from the Hughes Aircraft Company (HAC) for the synchronous-orbit communications satellite program in April, 1963. HAC engineers had had time to evaluate the OSM technology and found it suited to their equipment construction, which was stripline and semi-rigid cable. They also concluded that the products probably could meet the very demanding National Aeronautics and Space Administration (NASA) specs.

A team from HAC representing engineering, quality control, manufacturing, and contracting/procurement visited Omni Spectra at the end of May, 1963, and proceeded to work out a program. HAC engineers wanted to use the new technology throughout the satellite: OSM for microwave, but a scaled-down version of OSM for lower frequency circuits, similar to the BRMM size. This entailed scaling the diameter down by a factor of about 0.7, and designing connectors for flexible cable.

The customer wanted prototype quantities of six new OSM and six OSSM (scaled-down OSM) connector types in three weeks, delivery certain. Omni Spectra accepted a purchase order that specified a penalty for being late, and a small bonus for delivery as scheduled. The bonus was collected, and a valuable working relationship was started. The first units were used largely for qualification of both series for HAC and, thereby, NASA qualification. Production quantity orders for such programs were seldom very large. However, the rewards for working with a large, competent customer were considerable—providing a reference for the new company and its products.

There was never any engineering or development support offered by a customer or governmental agency and none was requested. Omni Spectra continued to seek and sort out suggestions and ideas from the field for designing improvements and product features. Interface mating dimensions were published at every opportunity. Specifications were rendered in MIL-C-39012 format and kept updated. Tools and assembly instructions were made available to allow duplication of factory results in the field insofar as possible. Other connector manufacturers came in gradually, beginning around 1964, and they largely conformed to the Omni Spectra interface and design—an example of voluntary coordination which led in 1968 to a standard under MIL-C-39012 as the type SMA. Repeatability of results on tests of this connector type have shown to be excellent [43], [44].

F. Focus on Attenuation per Wavelength, not Attenuation per Unit Length

Figs. 2–4 illustrate an important point regarding microwave circuit design and layout, which applies to product designs discussed in previous sections. For a given transmission-line size, the attenuation per unit length increases with frequency, but the attenuation per wavelength decreases [37]. This says: keep the length short and, where possible, scale the length down with wavelength. The unloaded Q, or Q_0, for a given line size thus increases with frequency.

Fig. 5 illustrates the three configurations of a two-conductor transmission line most commonly used in microwave circuits, components, and assemblies: coaxial line, stripline, and microstrip. Fig. 6 compares smaller size microstrip transmission line in performance to 0.34-in semi-rigid cable. Figs. 2–6 are taken from [42], prepared in 1965. The term Gc has since been replaced by GHz. Note that the dielectric material or microstriplines illustrated in Figs. 5 and 6 was assumed to be Teflon. Composite materials have since become available which come near to

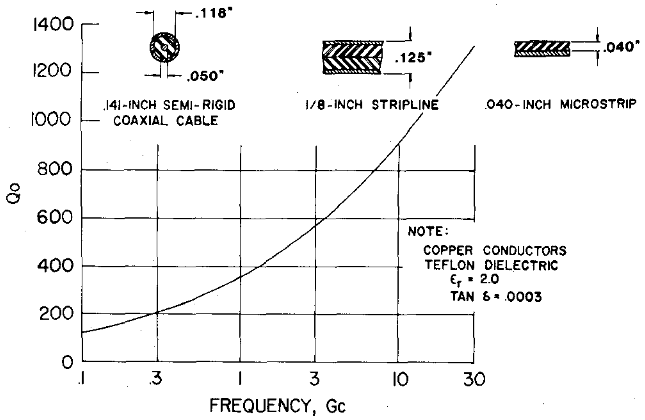


Fig. 4. Unloaded Q of coaxial line versus frequency for three line sizes. The vertical dashed lines indicate the frequency at which the particular size of transmission line can support a higher order mode.

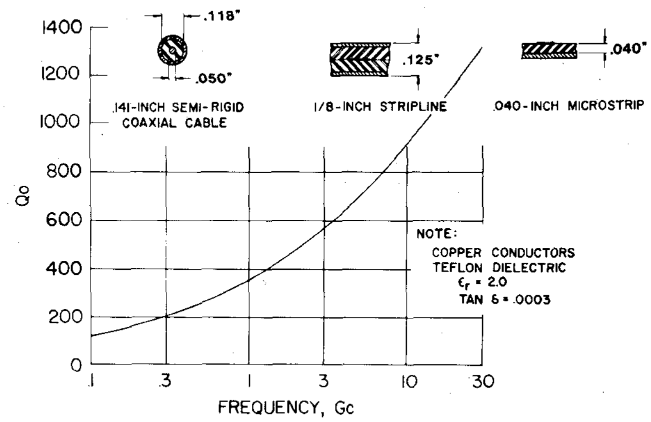


Fig. 5. Unloaded Q of 0.141-in semi-rigid coaxial cable, 1/8-in stripline, and 0.040-in microstrip. The unloaded Q is identical for each at any given frequency.

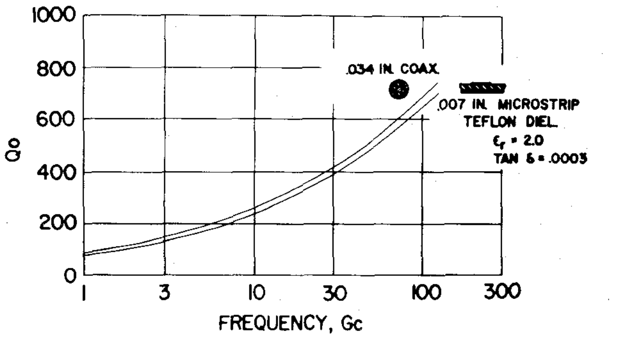


Fig. 6. Unloaded Q of subminiature microstrip and of subminiature coaxial line.

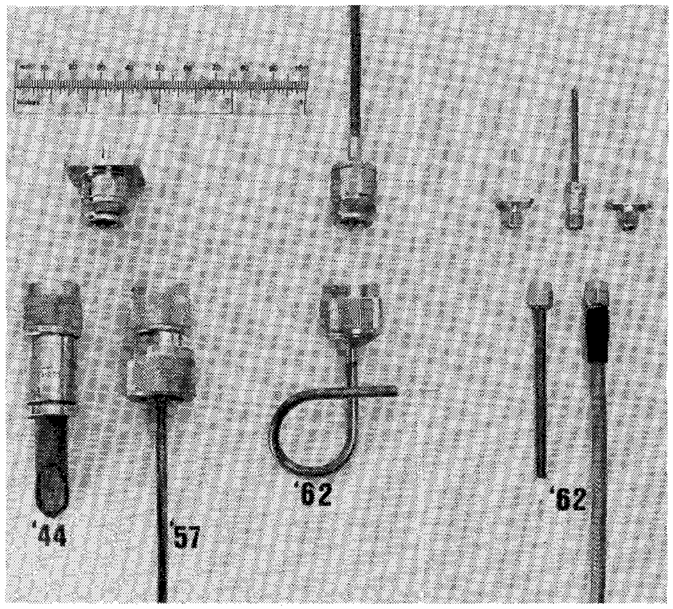


Fig. 7. Comparison of coaxial connectors and cables. From left, type N, UG-21/U connector (circa 1944) on RG-9/U coaxial cable of polyethylene dielectric and double braid outer conductor; above, type N, UG-53/U panel mount connector; type N connector with modified internal construction to improve microwave performance up to 12 GHz, shown mounted on 0.141-in semi-rigid cable (circa 1957); constant-impedance type N connectors (1962) with internal parts and cable attachment redesigned for broad-band, low VSWR performance to 18 GHz; and on right, OSM connectors (1962).

matching the parameters assumed. Several companies supply printed circuit board materials suitable for higher frequency microwave work which make use of glass fibers embedded uniformly in Teflon. The resulting composites have a dielectric constant ranging from 2.2 to 2.4 compared to around 2.0 for Teflon. The loss tangent is not as good but the mechanical properties are excellent, and use at temperatures as high as 150°C is feasible. Newer composites making use of Teflon show promise in maintaining a low dielectric constant with a loss tangent rivaling that of Teflon.

G. A Precision Type N Connector Design

The Omni Spectra founders hedged their bets in 1962 with a coaxial component line of conventional size using type N connectors. That effort was dropped in favor of concentrating on OSM products. Work on the type N configuration was not a lost cause, however, since the experience showed just how good the type N connector design could be made as a microwave device. The new design was broadband, low VSWR, and usable to 18 GHz, the upper frequency limit being set by the possibility of a higher order mode [45]. This type N design was first used in a between-series type N to OSM adapter (see Fig. 8). The results were excellent and it was discovered just how short such an adapter could be: less than 1.3-in (33-mm) overall length. The very short length and broad-band, low VSWR performance of both adapters and connectors were achieved by use of a single step in both the inner and outer conductor, maintaining 50-Ω impedance throughout, and compensating for the capacitance of the step with the inductance of a short length of high-impedance line formed by offsetting the steps. This design gives the shortest possible transition and gives excellent broad-band performance for line size steps of at least 1.6:1. This was followed by physically short, low VSWR type N connectors for use on semi-rigid cable (see Fig. 7). Between-series adapters accommodating all of the commonly used coaxial connectors, with specified electrical performance, were introduced in due course. The adapters proved to be very popular products.

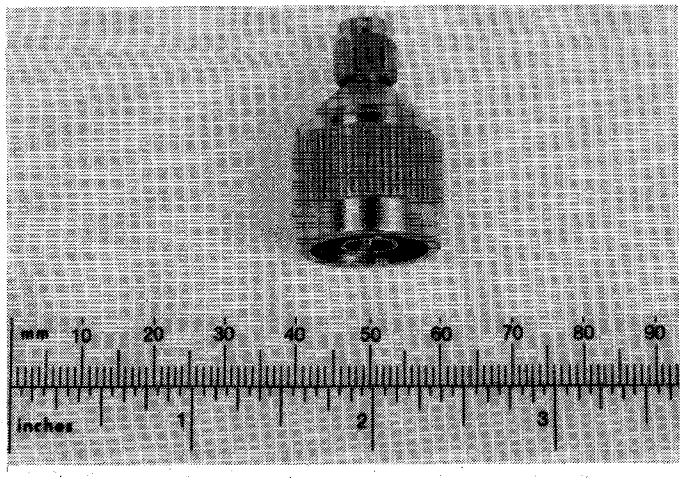


Fig. 8. Between-series adapter, type N to OSM.

IV. 1966 AND BEYOND

Industry acceptance and rapid growth in use of the new technology is illustrated by a product survey in 1966 [46] of Miniature Coaxial Components, which compared survey results on components and connectors with a similar survey one year earlier [39]: "This year 104 companies—23 more than in 1965—sell miniature components." "Today 18 firms manufacture connectors that mate directly with OSM/BRM; there were only 9 in 1965."

The growth in sales of coaxial components was such that total industry-wide dollar sales volume reached and passed that of waveguide components in 1967. The growth occurred for a complex and intertwined set of reasons. Most of the market had already been taken from the traditional coax products (10 GHz and below) because of size advantage, but especially because of better performance. The market was also being taken from waveguide products at all microwave frequencies (except in circuits carrying high power), often in retrofitting more elaborate functions into a given space. Coax technology was also finding new markets, such as applications in airborne and space vehicles, where the technology was vital.

The most important complementary happening was the advent of solid-state microwave semiconductor devices—diodes and transistors—in small, flat packages compatible with miniature circuits. Installing the semiconductors required access to the circuit, and microstrip construction (conducting strip and one ground plane) allowed that convenience. A result was the hybrid microwave integrated circuits, or MIC modules. These modules often required sealed enclosures, and the use of impedance matched hermetic-seal connectors (first introduced in 1963) grew rapidly—in a variety of configurations. One trend of this integration has been the packaging together of numerous components and devices to form a subsystem or supercomponent. Isolation to prevent unwanted coupling onto both RF lines and dc lines is important, taking account of the fact that RF signal propagation in the enclosure is not restricted to the microstrip transmission line. Other possible dominant modes of propagation must be taken into account and dealt with [48]. One trend in system integration has been to make plug-in types of MIC modules, with both RF and dc connectors located on one side of the housing. Available push-on, blind-mating RF coaxial connectors are usable at frequencies at least up to 18 GHz with low VSWR and low RF leakage.

Performance improvements have been made in flexible coax cables so as to render them relatively noise free. In one design, the outer conductor consists of a single layer of wires in a rather long-pitch spiral, in a manner similar to that described in [11]. The spiral may be supported by basket-weave braided wire or just the plastic jacket. Another design makes use of very thin, flat strips of metal in a basket-weave pattern, giving far fewer crossing contact points to give varying contact resistance when flexed.

Interest in higher microwave frequencies developed slowly at first and the market was thin, but progress was steady. The OSM/SMA connector can be used to 26 GHz. Some microwave market developed for OSSM primarily because of its smaller diameter but also because it is usable to still higher frequencies. During the late 1960's, the dollar volume of sales of OSSM connectors was about 10 percent that of OSM at Omni Spectra. A *Ka*-band (26–40 GHz) waveguide to OSSM coax adapter was designed and delivered in 1964. Other manufacturers introduced various components and test equipment using the OSSM interface, although no attempt was made at standardization of the OSSM.

The use of microstrip construction for hybrid integrated circuits up to 140 GHz is especially interesting [49], [50]. Quartz is used as the dielectric. At 100 GHz (3-mm wavelength), a dielectric thickness of 0.004 in (0.10 mm) is typically used, with conductor line-width twice that value to get 50-Ω impedance. Circuit connections and instrumentation presently used are waveguide. *W*-band waveguide for example is specified for 75 to 110 GHz. Ridged waveguide can be used in applications requiring greater bandwidth. On the other hand, the 0.034-in (0.86-mm) semi-rigid cable (Figs. 4 and 6) is usable dc to 135 GHz.

A major milestone in test instrumentation was the introduction around 1967 of microwave network analyzers controlled by digital computers. With the 7-mm precision coaxial connectors which had become available, the measurement of impedance, amplitude, and phase (with residual error removed) could be made to 18 GHz. The physically short between-series coaxial adapters with controlled mechanical tolerances proved to be phase matched in random selection of pairs. Using them, measurements could be made on components with any of the commonly used connectors. Industry work was done on a precision connector in the 3.5-mm-size range, about one-half the size of the 7-mm connector, and designed for use at frequencies to approximately 36 GHz, but no standard has been adopted. Commercially available test equipment with precision air–dielectric interface connectors which mate with the SMA connector is specified for use to 36 GHz. More recently, test instrumentation usable to 45 GHz, with still smaller precision connectors also mateable with SMA, has become available. It is difficult to forecast how far the trend may move in the use of coax instrumentation at millimeter frequencies. Considering that use of coax to 26 GHz was a visionary idea in 1962, the trend may yet have a way to go.

Acknowledgment

The author has searched many sources in preparing this paper, including an effort to contact individuals who would seem to have first-hand knowledge of, or leads to, information on early work, especially of the 1930's and early 1940's. The brief statements referring to conversation or correspondence with them can in no way do justice to the scope and degree of contributions made by them, and for this the author asks their indulgence. His limitations and the limitation of space and scope prevent this paper from being a complete history of microwaves, or of radar.

The contributions of former colleagues is especially acknowledged, realizing that most of their contributions are not hearalded in the published literature but in the products which they produced and the way in which those products may have influenced the course of microwave technology and applications.

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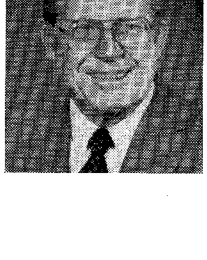

John H. Bryant (M'50–SM'52–F'67) received the B.S.E.E. degree from Texas A&M University in 1942, and served three and a half years on active duty in the U.S. Army Signal Corps. As a member of Group 12 of the Electronics Training Group, he was sent to England for school and operational training in radar. On completion of the intense course at the Royal Air Force (RAF) school in Cranwell, Lincolnshire, he was posted as Commanding Officer of a British radar station, RAF Skendleby, on the coast of Lincoln-

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Microwave Printed Circuits—The Early Years

ROBERT M. BARRETT

I. Introduction

An IMPORTANT MILESTONE in microwave technology was the development of the "microwave printed circuit" (MPC), or flat-strip microwave components, fabricated by conventional printed-circuit techniques. This development freed the microwave designer from the constraints, and often prohibitive costs, encountered when designing complex circuitry either in waveguides, coaxial lines, or two-wire transmission systems. The costs and complexities of fabrication often discouraged the development of innovative and complex circuits using these traditional wave guiding or transmission structures.

The purpose of this paper is to present an outline of the concept of "microwave printed circuits" as it was originally conceived, and to add a few brief historical comments on the facts surrounding its conception and initial reduction to practice. Available space precludes a treatment of the current state of the art. This treatment is, therefore, limited to the beginnings and the early trends and applications of MPC.

The microwave printed circuit as described herein is an extension of the well-known techniques which were of such importance in the lower frequency regions where lumped circuit elements are practical—actually it is a marriage of this low-frequency printed-circuit technology and the powerful technology of the coaxial and waveguide microwave systems, where distributed circuit elements have replaced lumped circuits. The new circuit configurations possessed many of the attributes of conventional printed circuits, such as light weight, low cost, ease of manufacture, miniaturization, ease of design, etc., along with their ability to be used at frequencies exceeding 10 000 MHz. The basis of the new technique was the planar coaxial transmission system that was developed during World War II. This development remained unpublished, was relatively unknown in the post-war period, and was not supported by adequate theoretical analysis.

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II. A Little History

A flat-strip coaxial transmission line was first used, insofar as this author was able to determine, by V. H. Rumsey and H. W. Jamieson and was applied to a production antenna system and power division network during World War II. A similar application to an experimental electromechanical scanning radar power distribution system was developed by Mr. John Ruze, an associate of this author, at the Cambridge Field Station of the United States Air Force. A commercial application of a planar coaxial system was the development of a "slotted line" by the Hewlett-Packard Co. Although the basic concept of a transmission system using a line—or strip—between two flat plates was thus in existence, it was thought of in massive terms of large plates or slabs, solid, flat, or cylindrical rods as the center elements, and was essentially to be used only as a special-case power transmission element.

The technique remained dormant until early in 1949 when, while trying to devise a new method of feeding a microwave "Wullenweber" antenna, it occurred to this author that not only could flat-strip coaxial lines, in a flat plate form, be employed to carry energy from point to point but they could also be used to make all types of microwave components such as filters, directional couplers,