THE WAVEGUIDE BELOW CUTOFF ATTENUATION STANDARD

David H. Russell
National Institute of Standards and Technology - Retired

Abstract - A semi-tutorial review of the history, development and application of waveguide below-cutoff attenuation standards is presented. A brief summary of the EM theory is followed by descriptions of the various designs implemented over a span of 60 years. Designs range from simplistic to elaborate electro-mechanical creations stretching the toolmaker's art yet ultimately dependent upon the primary standard of length.

Introduction

In the current measurement world of Automated Vector Network Analyzers based on multiport reflectometers, it is easy to lose sight of some of the underlying basic standards of power, impedance and **attenuation**. The waveguide below-cutoff attenuator (WBCO) propagating a single evanescent mode down a uniform waveguide is nearly an ideal primary standard since incremental attenuation can be closely predicted from only a knowledge of its dimensions within minor restraints of frequency of operation and deviation from losslessness of the material used for fabrication of the guide. Using the device at an intermediate (IF) frequency such as 30 MHz with linear mixing to higher microwave and millimeter wave frequencies, attenuation transfer standards may be calibrated to nearly any desired degree of precision and accuracy. Techniques are required to insure the validity, in practice, of the theoretical computations used in designing a standard WBCO attenuator. Since attenuation is basically the determination of a dimensionless ratio, methods have been devised using multibranch networks to independently assess the minor errors in WBCO devices due to deviation from losslessness of the guide material and unsuppressed multimode propagation. Other independent methods such as direct power ratio and dc substitution are often used. At NIST, exact attenuation steps based on a superconducting quantum interference device (SQUID) were successfully used to validate the estimated uncertainty of a WBCO attenuation standard.

History

The earliest realizations of this WBCO technology date to the 1930's when Harnett and Case described the use of two moving inductors in a circular tube to test receiver sensitivity [1]. Applications were refined during World War II at the MIT Radiation Laboratory in the United States where cutoff attenuators with both circular and rectangular cross-sections were fabricated to 24 Ghz [2].

This work was rapidly advanced from 1945 through 1950 by Gainsborough, Grantham, Freeman, Wheeler, Brown, Barlow and Cullen who refined the earlier crude mechanical designs of WWII and applied appropriate corrections so they could be used as true standards of attenuation [3,8].

0-7803-4603-6/97/$5.00 (c) IEEE

The 1950's through the 1970's saw the major thrusts in WBCO design innovation and its establishment as a true primary standard of attenuation through the efforts of such pioneers as Allred, Hollway-Kelly and Weinschel [9,14]. These efforts pushed the physical limits of materials and the limits of length metrology to a point of diminishing returns. These "ultimate" WBCO attenuators were developed at NIST (NBS) in the United States, NPL in Great Britain, CSIRO in Australia and in the commercial sector at Weinschel Engineering in the United States. In later years (1980's), an automated "compact" version of the NPL primary standard attenuator was commercially manufactured by Techtest Ltd. Weinschel Engineering developed and marketed a similarly compact automated dual-frequency WBCO attenuator during this period.

Theory

A cutoff attenuator may be designed for either a TM or a TE mode of transmission. In designs using the TM mode the guides are usually terminated in some form of disk where the coupling is capacitive. In designs using the TE mode the guides are terminated in a coil or loop and the coupling is inductive.

A waveguide section, excited in one mode by a sinusoidal signal at a frequency below cutoff, has an exponential decay of field strength along its axis. The rate of decay may be closely predicted from a knowledge of the cross-sectional dimensions of the guide. A moving probe which couples to the field will therefore have a predictable output variation. The entire assembly constitutes a standard of attenuation.

Circular WBCO attenuators are operated in the dominant TE_{11} mode. Undesired modes can be suppressed by metallic strips or dielectric mode filters.

At lower frequencies skin effect increases the effective electrical radius of the guide and contributes large uncertainties, especially since machining affects wall conductivity. For this reason and the possibility of leakage through the attenuator walls, WBCO attenuators are seldom used below 1 MHz. The upper frequency limit is determined by the cutoff frequency and the necessity to operate well below cutoff to decrease the frequency dependence of the attenuator. At extremely high frequencies (above 1 Ghz), required guide dimensions become so small that the necessary mechanical tolerances for an accurate standard cannot be readily achieved.

The most important considerations for the circular WBCO attenuator relate to dimensional tolerances in the guide and the resolution and accuracy with which the relative displacement of the exciting and pickup coils can be measured. Typical commercially available WBCO attenuators for use at IF frequencies have inside guide diameters ranging from 0.75 to 1.5 inches for corresponding attenuation rates of 40 to 20 decibels per inch displacement of the moving coil. To keep uncertainties to 0.005 decibel per 10 decibel increment requires tolerances of a few ten-thousanths of an inch. Tolerances of the same order are required in measuring displacement. The traditional lead screw and mechanical counter have been replaced by precision ruled scales and optical encoding devices. Much greater precision and repeatability has been achieved using linear interferometers.

The theoretical computations and corrections for conductivity, permeability, and dielectric constant have been independently verified by several methods, one of the most accurate of them being a superconducting quantum interference device or SQUID [15].

Devices

Most WBCO attenuators of extreme precision and accuracy have been constructed to operate at or near 30 MHz. Descriptions follow of WBCO attenuators which were fabricated in the United States, England and Australia, and represent the vast majority of precision devices of primary standards quality.

0-7803-4603-6/97/$5.00 (c) IEEE

United States - NIST (NBS)

Historically, the WBCO attenuators fabricated at NIST progressed from devices with guide diameters of one-half inch and a corresponding attenuation rate of about 60 decibels per inch through a series of devices with guide diameters of about 1.5 inches with an attenuation rate of 20 decibels per inch to the current national primary reference standard with a guide diameter of 3.2 inches and an attenuation rate of 10 decibels per inch.

The earliest (60 dB/inch) models were totally dependent upon a finely machined lead screw, a mechanical turns counter and a circular ruled dial for reading out incremental attenuation. These could be read to 0.05 decibel and had accuracies of the same order.

The next series of devices moved to 20 decibels per inch of displacement and were refined (several models were copied and sold by private industry) over 3 decades from the mid 1950's to the mid 1980's. The precision lead srew was combined with a rack and detent mechanism to permit steps of 10 decibels and fine adjustment from each detent point. The lead screws became ever more precise and the readout system employed preloaded ball-bearing nuts, ultra precise gear trains and motor drives for rapid setting.

Additional improvements were made by incorporating precision ruled scales and optical readouts to permit direct reading to 0.001 decibel and interpolation to 0.0001 decibel. Accuracies approached 0.005 decibel per 10 decibel increment. Some of the final versions of these WBCO attenuators were even retrofitted with corner cube reflectors and linear position encoding interferometers.

A primary reference 30 MHz WBCO attenuator was required at NIST to calibrate improved devices. This attenuator was designed and fabricated by Allred and Cook in 1960 [11] and updated and reevaluated over succeeding years by Russell, Adair, Marler and Jargon [18,19]. The attenuator is vertically mounted, has an attenuation rate of 10 decibels per inch with a guide diameter of 3.19725 inches using a laser interferometer for displacement measurement.

United States - Weinschel Engineering

A series of precision WBCO attenuators and associated attenuation measurement systems were manufactured and marketed at the same time NIST was developing its series of devices. Although the Weinschel designs employed circular guide, they were fabricated of stainless steel rather than the brass and copper of NIST, NPL and NML. This required a larger correction for conductivity as well as a permeability correction. The material had one substantial advantage over other materials - it could be honed with superior precision and was very stable with time. The uncertainties associated with these attenuators were comparable to the secondary standards developed at NIST and of the order of 0.001 decibel per 10 decibels.

In the 1980's Weinschel developed a much more accurate (0.0002 - 0.0003 decibels per 10 decibels) dual-frequency (1.25/30 MHz) attenuator that was computer controlled and employed a laser interferometer [20].

Australia - CSIRO (NML)

Two of the most significant WBCO attenuators of primary standards laboratory quality were developed at the National Measurement Laboratory (NML) in Australia. The first, by Hollway and Kelly [13] was developed in 1963 and featured a silver-layered guide with an attenuation constant of 20 decibels per inch and operated at a frequency of 31.25 MHz. Displacement was measured with a precision ruled scale combined with an optical readout. Uncertainty in measuring a 10 decibel step was estimated to be 0.001 decibel.

0-7803-4603-6/97/$5.00 (c) IEEE

The second attenuator used an electroformed guide and a laser interferometer for displacement measurement was described in 1984 and yielded a resolution of 0.0001 decibel with and extimated uncertainty of 0.0005 decibel in 10 decibels. This attenuator was vertically mounted like the NIST standard and was one of the first described to use remote positioning and control implementing the IEEE 488 computer bus [21].

United Kingdom - NPL

The National Physical Laboratory in England developed a similar WBCO attenuator using a laser interferometer and an air supported moving piston to eliminate wear in the circular electroformed copper guide. The moving piston and coil assembly was unique in incorporating an RF oscillator which eliminated the problems associated with flexible coaxial cables. A diode detector and feedback loop were incorporated to insure constant RF level to better than 0.0002 decibel over 10 minutes [22].

This non-portable design was modified by Holland and Yell into a compact "folded" horizontal design using a laser interferometer and air-bearing piston during the late 1970's which subsequently formed the basis in the mid 1980's for a commercial version manufactured by Techtest Ltd. The estimated uncertainty is approximately 0.0002 decibel in 10 decibels.

Validation of uncertainty

One of the key issues in determining the accuracy of WBCO attenuators is how to cross-check the uncertainty of the value assigned to the attenuation constant computed using basic EM theory and estimated or measured guide size, conductivity and permeability. In measuring attenuation a standard is not actually required, as basically it is the determination of a dimensionless ratio. Most of these methods are based on obtaining known signal ratios by "power division", adding, and subtracting of signals. Some of the other approaches involve direct power ratio measurement using dc substitution and fixed voltage steps based upon the Josephson junction effect (SQUID's)

A major attenuation intercomparison at 30 MHz was conducted in 1978 under the auspices of the BIPM (Bureau of International Weights and Measures) and thoroughly validated the theory underlying the uncertainties assigned to these devices in primary laboratories all over the world. The results of the intercomparison show splendid agreement among the participating laboratories which included France, Germany, Hungary, Sweden, England, Australia, United States and Japan.

Conclusions

The waveguide below cutoff attenuator has established itself as a primary standard of great dynamic range which was brought to a peak in design technology in the 1980's.

Limitations on the physical properties of materials, escalating costs and the advent of vector network analyzers has essentially terminated further refinements in the design and implementation of these devices. At this time, their use in ultimate form is confined to the primary standards laboratories.

A review of their development history is a review of the history of standardization and measurement itself.

References

[1] D. E. Harnett and N.P. Case, "The design and testing of multi-range receivers, "*Proc. IRE*, vol.23,pp. 578-593, June 1935

[2] R N. Griesheimer, "Microwave attenuators. Cutoff attenuators," in *Technique of Microwave Measurements*, M.I.T. Radiation Lab. Ser., vol 11. New York:McGraw-Hill, 1947,ch.11,pp. 685-719.

[3] G.F. Gainsborough, "A method of calibrating standard-signal generators and radio frequency attenuators," *J. IEE (London)*, vol.94,pt.III, pp. 203-210, May 1947

[4] J.J. Freeman, "Theory and design of a cavity

attenuator." *J. Res. NBS*, vol.40, pp. 235-243, March 1948.
[5] R. E. Grantham and J.J. Freeman. "A standard of attenuation for microwave measurements," *Trans. AIEE*, vol.67,pt.I, pp 329-335, June 1948
[6] H.A. Wheeler, "The piston attenuator in a waveguide below cutoff," Wheeler Labs., Great Neck, N.Y., Mono. 8, January 1949.
[7] J. Brown, "Corrections to the attenuation constants of piston attenuators," *Proc. IEE (London)*, vol. 96, pt. III, pp. 491-495, November 1949.
[8] H. M. Barlow and A.L. Cullen, *Microwave Measurements*. London: Constable, 1950, pp. 242-254, 384-388.
[9] C. M. Allred, "Chart for the TE_{11} mode piston attenuator,"*J. Res. NBS*, vol. 48, pp. 109-110, February 1952.
[10] D. M. Kerns and R.W. Hedburg, "Propagation constant in rectangular waveguide of finite conductivity," *J. Appl. Phys.*, vol 25, pp. 1550-1551, December 1954.
[11] C. M. Allred and C.C. Cook, "A precision RF attenuation calibration system," *IRE Trans. Instrumentation*, vol. I-9, pp. 268-274, September 1960.
[12] L.A. Birger, "Nonlinearity of cutoff attenuators due to the effect of loading, "*Ismeritel'naya Tekhnika*, no. 11, pp. 59-61, 1960
[13] D.L. Hollway and F.P. Kelly, "A standard attenuator and the precise measurement of attenuation," *IEEE Trans. Instrumentation and Measurement*, vol. IM-13, pp. 33-44, March 1964.
[14] B.O. Weinschel and G.U. Sorger, "Waveguide below-cutoff attenuation standard," *Acta IMEKO III*, pp. 407-424, 1964
[15] R.T. Adair, M.B. Dimmonds, R.A. Kamper and C.A. Hoer, "RF attenuation measurements using quantum interference in superconductors," *IEEE Trans. Instrumentation and Measurement*, vol. IM-23, no. 4, pp. 375-381, December 1974.
[18] R.T. Adair and D.H. Russell, "A calibration service for 30 MHz attenuation and phase shift," *NBS Measurement Services Special Publication, no. 250-32, April 1988.*
[19] J.A. Jargon, "A revised uncertainty analysis for the NIST 30 MHz attenuation calibration system," *Measurement Science Conference*, Pasadena, California 1994.
[20] D.H. Russell and W. Larson, "R.F. attenuation," *Proc. IEEE*, vol. 55, no. 6, pp 942-959, June 1967.
[21] B.O. Weinschel, "A new attenuation standard uses laser interferometer," *Microwave Journal*, vol. 27, no. 8, pp. 145-148, August 1984.
[22] T.E. Cousins and H. Kobler, "A 30 MHz standard attenuator," *JEEE Australia- IE Aust. & IREE Aust*, vol. 4, no. 1, pp. 1-5, March 1984.
[23] J.M. Steele, C.R. Ditchfield and A.E. Bailey, "Electrical standards of measurement, part 2: RF and microwave standards," *Proc. IEE*, vol. 122, no. 10R, IEEE Reviews, pp. 1037-1053, October 1975.