A knowledge of the field components should also prove useful in the design of mode launchers, such as between microstrip and slot-line [5], [16], and between coplanar waveguide (CPW) and slot-line [11].

Besides, it should also prove useful in the study of coupling between a slot-line and a cylindrical dielectric resonator. Goebel and Schieblich [12] have studied the coupling between a slot-line and a cylindrical dielectric resonator. Their studies show that the coupling is efficient when the slot runs tangential to the resonator and when the edges of the resonator extend into the slot. Such a study should also prove useful in filter applications [13].

Finally, a knowledge of the current distribution on the metal surfaces should prove useful in the design of slot-line antennas [10], [14], [15]. The lower ground plane, besides being useful in slot-line antennas, can also act as a heat sink in applications involving solid-state devices.

VII. Conclusion

The paper presents expressions for the odd- and even-mode electric field components and the magnetic field components in the air and dielectric regions of broadside-coupled slot-lines. These expressions have been numerically evaluated and the fields in the cross section and the longitudinal section are illustrated. Besides, the computed current paths on the metal surfaces and the tangential magnetic field are illustrated. The magnetic field in the longitudinal section, and in the plane of the slot, is elliptically polarized.

Acknowledgment

The author wishes to thank L. A. Robinson of Stanford Research Institute and S. B. Cohn of S. B. Cohn Associates for providing the necessary references. The author is also grateful to S. B. Cohn for several helpful communications on slot-line. The author is also grateful to the reviewers for their helpful comments.

References

[1] S. B. Cohn, "Slot-line on a dielectric substrate," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-17, pp. 768–778, Oct 1969.

[2] G H. Robinson and J. L. Allen, "Slot-line application to minature ferrite devices," *IEEE Trans Microwave Theory Tech.*, vol MTT-17, pp. 1097–1101, Dec. 1969.

[3] N. Ogasawara and M. Kaji, "Coplanar-guide and slot-guide junction circulators," *Electron. Lett.*, vol. 7, pp 220–221, May 1971.

[4] M. De Vecchis, L. Raczy, and P. Gelin, "A new slot-line broadband isolator," in *Proc. 3rd Eur Microwave Conf.*, vol. 2, B.9.6, Sept. 4–7, 1973.

[5] L. Courtois and M. De Vecchis, "A new class of nonreciprocal components using slot-line," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-23, pp. 511–516, June 1975.

[6] S. B. Cohn, "Slot-line field components," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-20, pp. 172–174, Feb. 1972.

[7] R. N. Simons and R. K. Arora, "Coupled slot-line field components," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-30, pp. 1094–1099, July 1982.

[8] R. N. Simons, "Suspended broadside coupled slotline with overlay," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-30, pp. 76–81, Jan. 1982.

[9] R. N. Simons, "Studies on microwave slot-line and integrated fin-line," Ph.D. thesis, Dept. Electrical Eng., Indian Institute of Technology Delhi, New Delhi, India, 1982.

[10] J. W. Greiser, "Coplanar stripline antenna," *Microwave J.*, vol 19, pp. 47–49, Oct. 1976.

[11] M. Houdart and C. Aury, "Various excitations of coplanar waveguide," in *IEEE MTT-S Int. Microwave Symp. Dig.*, April 30–May 2, 1979, pp. 116–118.

[12] U. Goebel and C. Schieblish, "Broadband fin-line circulators," in *IEEE MTT-S Int. Microwave Symp. Dig.*, June 14–19, 1982, pp. 249–251.

[13] J. K. Plourde and C. L. Ren, "Application of dielectric resonators in microwave components," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-29, pp. 754–770, Aug. 1981.

[14] S. N. Prasad and S. Mahapatra, "A novel MIC slot-line antenna," in *Proc. 9th Eur. Microwave Conf.*, Sept. 17–21, 1979, pp. 120–124.

[15] P. A. R. Holder, "*X*-band microwave integrated circuits using slotline and coplanar waveguide," *Radio Electron. Eng.*, vol. 48, pp. 38–42, Jan./Feb 1978.

[16] J. B. Knorr, "Slot-line transitions," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-22, pp. 548–554, May 1974.

Radar-Echo Location of Conducting Spheres in Waveguide

P. I. SOMLO, SENIOR MEMBER, IEEE

Abstract —**The radar-echo locations of conducting spheres placed in the center of the broad wall of a rectangular guide were measured using the synthetic-pulse technique. The measuring instrument was a six-port reflectometer whose results in the frequency domain were transformed digitally into the time domain. It was found that, as the size of the spheres was reduced, the radar-echo locations approached the center of the spheres in an oscillatory manner. The findings are somewhat unexpected, as the echo centers for some sphere sizes appear to be farther away from the source than their physical centers.**

I. Introduction

It has been reported that conducting spheres placed in waveguides have the special property that their reflection coefficients are quasi-constant with frequency [1]. It has also been shown empirically that this is true for all sphere sizes, with diameters nearly up to guide height. The magnitude of the reflection coefficient $|\Gamma|$ of a small sphere varies as the volume of the sphere. This finding has been confirmed theoretically using a perturbation method [2].

Because conducting spheres produce a quasi-constant magnitude of reflection coefficient and may easily be positioned in a waveguide, they are useful as special tuning elements which offer wide-band compensation. Arg(Γ) may be adjusted by axial positioning, and $|\Gamma|$ by lateral positioning. Steel balls (bearing balls) may be moved and held in place by small external magnets. In the Locating Reflectometer [3], for instance, the directivities of both the reference and the measuring directional couplers were increased over the whole *X*-band by placing small spheres near the start of the multi-hole coupling region. It has been shown [3, fig. 9] how the internal reflections of a horn antenna were reduced to a negligible level over the whole *X*-band by suitably positioning (and gluing) four steel balls near the throat of a horn antenna.

The purpose of this investigation was to measure the effective locations of conducting spheres placed in the center of the broad wall of rectangular waveguide. One may define a number of ball-position criteria. One such definition may be position of a lumped susceptance producing the same $|\Gamma|$ as a ball. This definition is physically inexact, since the larger balls cannot be regarded as lumped obstacles. A similar definition would be to use arg(Γ). Another definition regards the balls to be positioned where $\mathrm{Re}\,\Gamma(t) = 0$, since the ball is assumed loss-free. Again, this

Manuscript received April 4, 1983; revised August 16, 1983.

The author is with CSIRO, Division of Applied Physics, P.O. Box 218, Lindfield, NSW 2070, Australia

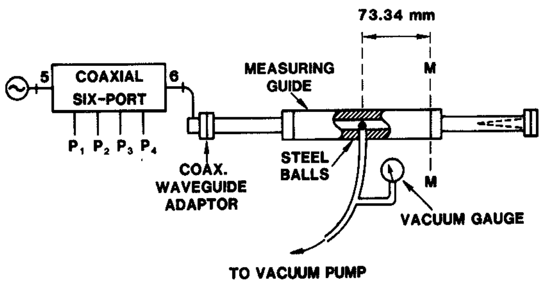

Fig. 1. Schematic diagram of setup to measure the reflection coefficients of steel balls. A 0.32-mm diam hole connected to a vacuum pump locates the balls. The six-port was calibrated at the plane of $M-M$ with waveguide standards.

definition is arbitrary, because the balls in general are distributed obstacles. The most meaningful definition of ball positions is the distance at which a radar measurement locates the maximum of the returned pulse. The present work obtained this result from a synthetic-pulse-type measurement using a six-port in the frequency domain, from which time-domain information was computed.

The present investigation was prompted by a discussion by J. Appel-Hansen [4] of the reflection centers of large spheres in the near-field, and the realization that no such information exists for conducting spheres in waveguides. The present work provides measured data for future theoretical studies.

II. Method of Measurement

Because the aim was to determine the effective location of the spheres with an uncertainty less than 0.1 mm, an accurate method of measurement was needed. For this reason, the recently described six-port reflectometer [5] was chosen as the reflection coefficient measuring apparatus, calibrated by the "$6\frac{1}{2}$ standards," redundant method. The coaxial six-port was connected to a coaxial/waveguide adaptor, followed by a straight section of a uniform guide, and then by a specially constructed measuring guide, as shown in Fig. 1. For accurate re-positioning of all the balls, the measuring guide had a small, 0.32-mm diam hole drilled in its central region, in the center of the broad wall. The hole was connected to a vacuum pump by a vacuum line equipped with a vacuum gauge. This gauge enabled the balls to be positioned with high repeatability by indicating a pressure drop when the balls were captured over the hole. The balls were inserted and removed from the measuring guide after removing the pyramidal matched load from the external sliding load housing guide.

The calibrated measuring plane of the six-port was the outside flange of the measuring guide, (plane $M-M$ on Fig. 1) to which the waveguide standards were connected. These were provided by five micrometer-driven offset short circuits, three positions of a sliding matched load, and three positions of a sliding load in a reduced height guide, which gave the intermediate reflection coefficient (magnitude only) standard.

In order to obtain as narrow a synthetic pulse as possible, the measurements were carried out over as wide a frequency band as possible (over the whole of the X-band). The six-port was calibrated at 11 frequencies ranging from 8.2 to 12.4 GHz, and the reflection coefficients of 11 balls were measured. Ball diameters varied from 2.44 to 10 mm. To reduce scatter due to noise and possible variations in contact resistance of the balls to the guide, the balls were repositioned three times and the average of the reflection coefficients was taken as the result. To reduce the effect of residual reflections from neighboring imperfections

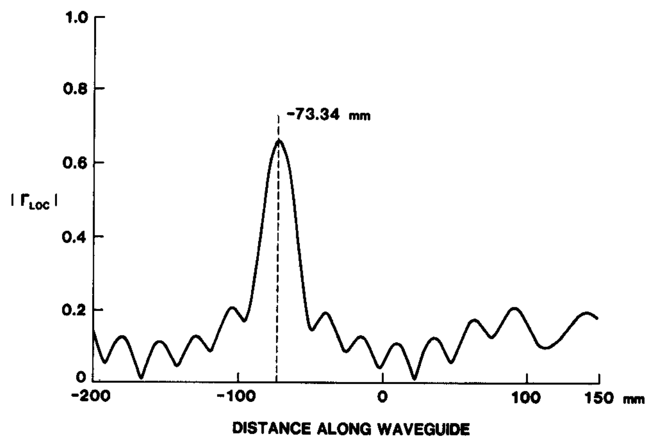

Fig. 2. Plot of the magnitude of the locating vector $|\Gamma(\text{time})|$ versus distance along the waveguide for a 5.54-mm diam ball.

(flanges, sliding load residuals, etc.), Γ (no ball), which was obtained by measuring without the ball, was subtracted from the average of three-Γ (ball) measurements, with the matched load returned to its position. Since the Fourier transforms of additive functions are additive, this operation was equivalent to subtracting the radar echoes of the background clutter from the radar echoes of the balls, without having to compute two Fourier transformations.

The Fourier transform of $\Gamma(f)$ (reflection coefficient in the frequency domain—the familiar concept) is $\Gamma(t)$ (the reflection coefficient in the time domain—not so familiar), which will be subsequently referred to as the "locating vector."

III. Results

Having measured the reflection coefficients of the balls, $\Gamma_{b,f}$ referenced to the plane $M-M$ at the 11 frequencies, the locating vectors were computed by referencing $\Gamma_{i,f}$ to different planes along the guide, and averaging these for a given ball, as outlined in [6]. A plot of the magnitude of the locating vector of a ball is shown in Fig. 2. The particular shape of the sidelobes is the result of the choice of frequencies at which $\Gamma_{b,f}$ were measured. Since our aim was to determine the radar-echo location of the balls, the peaks of the locating vectors had to be found. Fig. 3 shows an expanded view of the peaks of all the locating plots. The exact positions of the peaks were found by a simple maximum-seeking procedure as the locating vector was computed.

Fig. 4 shows the result, which is the maximum-of-echo-distance versus ball diameter. This curve shows, as expected, that large balls appear to be closer to the source than their centers, since the front hemisphere is illuminated, and an almost full reflection is produced, suggesting a reduced significance of the shadowed hemisphere. It is also interesting to remember that, for plane waves in the optical limit, when the diameter is much larger than the wavelength, the echo-center tends to be at half radius, towards the source [4]. The interesting finding was, however, that for some intermediate-sized balls, the echo-maxima appear to be on the far side of the balls. As the ball diameter is reduced, Fig. 4 shows the echo-positions approaching the physical location of the ball centers.

A probable qualitative explanation of the finding that some intermediate-sized balls produce radar echos located (in absolute terms of distance) on the far side of the balls is the following. A ball may be modeled over a wide band as tapered sections of guides axially symmetrical about the ball center, with a shunt

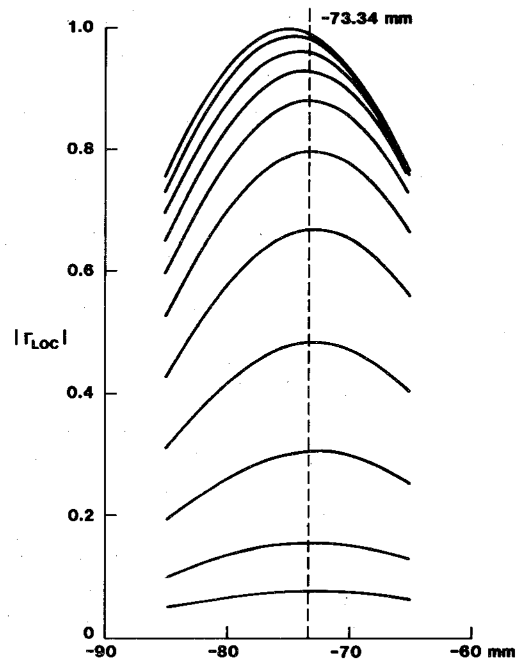

Fig. 3. Expanded view of the peaks of the magnitudes of the locating vectors for the balls measured versus distance. The shift of the peaks toward the source for large balls is easily seen.

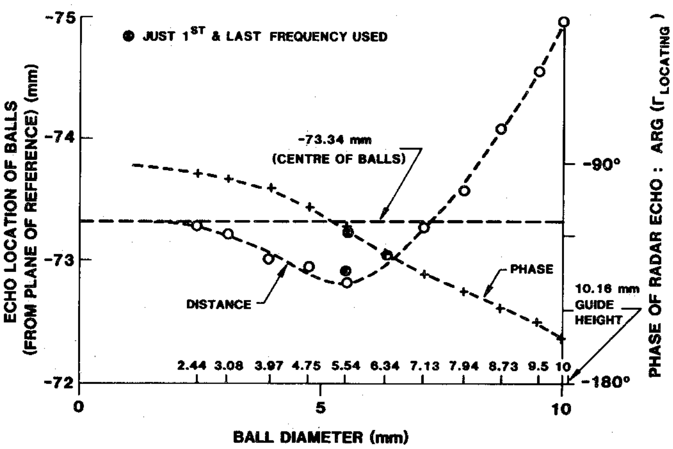

Fig. 4. Computed positions of the peak of the radar-echo, and arg(Γ(time)) versus ball diameter. It is seen that small balls appear to be farther away than their centers. Echoes of large balls move closer to the source. As a cross-check, the points indicated by × were computed using the first and last frequencies only.

susceptance in the center. Since the guide wavelength in the tapered section lengthens, the shunt susceptance appears to be farther away (group-delay is increased). For very large balls, this taper is very severe (guides tending toward cutoff), and dominates over the effect of the shunt susceptance and thus puts the reflection forward.

The experimental uncertainty in the echo locations is difficult to state, but repeated measurements produced very similar results. The individual departures of the points on Fig. 4 from the smooth fitted curve give an indication of the scatter. As a cross-check, the point corresponding to the largest, seemingly anomalous, echo location was computed using only the two extreme frequencies of the set of eleven, and reproduced the

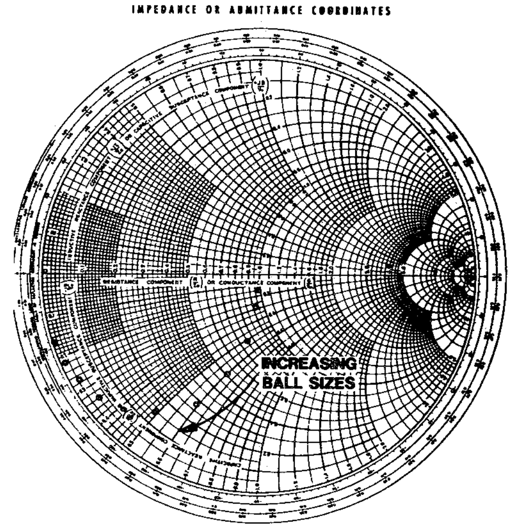

Fig. 5. The locating vector evaluated at its maximum, plotted on the Smith-chart for varying ball sizes. A resemblance to a capacitive obstacle is recognizable. Note that the locating vector is in the time domain.

trend of the results of the full set, as shown in Fig. 4.

In Fig. 4, the computed phase of the locating vector is shown at the echo-maxima. For small balls, the phase tends toward $-90°$, meaning that small balls may be regarded as lumped capacitive obstacles, whereas large balls exhibit phases which approach $180°$, the expected value for an impedance which approaches a short circuit.

The Smith-chart plot of the complex locating vector (Fig. 5) indicates a quasi-capacitive behavior for all ball sizes. The departure from purely capacitive loading is attributed to the breakdown of the lumped element approximation as the balls become larger and the impedance is distributed along the waveguide.

References

[1] P. I. Somlo, "Conductive contacting spheres on the centre of the broad wall of rectangular waveguides," *Electron. Lett.*, vol. 8, no. 20, 1972.

[2] J. H. Hinken, "Conducting spheres in rectangular waveguides," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-28, July 1980.

[3] P. I. Somlo, "The locating reflectometer," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-20, Feb. 1972.

[4] J. Appel-Hansen, "Near-field cross sections and reflection centres for large spheres and plates—A fundamental analysis," *Tech. Univ. of Denmark*, Report R231, 1980. Also in *Antenna and Scattering Seminar*, (NML Australia) 1982.

[5] P. I. Somlo and J. D. Hunter, "A six-port reflectometer and its complete characterization by convenient calibration procedures," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-30, Feb. 1982.

[6] P. I. Somlo, "Time-domain reflectometry from Smith-chart plotting," *Electron. Lett.*, vol. 9, no. 10, 1973.

Propagation on a Sheath Helix in a Coaxially Layered Lossy Dielectric Medium

MARK J. HAGMANN, MEMBER, IEEE

***Abstract*—Radial and axial dependence of the azimuthally symmetric fields in each coaxial layer may be expressed in terms of modified Bessel**

Manuscript received April 26, 1982; revised August 3, 1983.

The author is with the Biomedical Engineering and Instrumentation Branch, Division of Research Services, National Institutes of Health, Bethesda, MD 20205