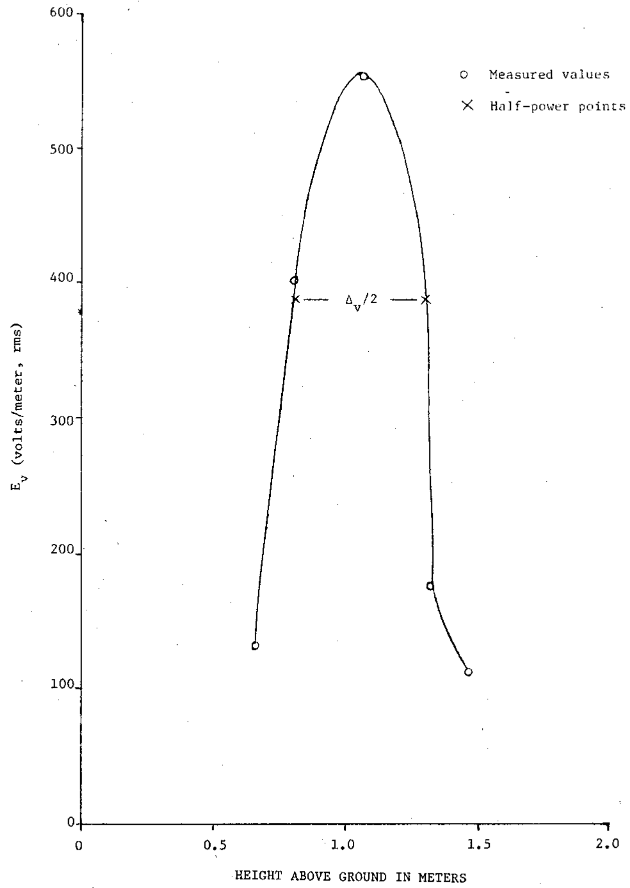

Fig. 4. Measured values of the vertical electric field component E_v from an RF sealer and application of the empirical equation.

V. Conclusions

An empirical relationship has been presented giving the whole-body-average SAR for a 180-cell block model of man exposed to near fields which roll off monotonically to negligible values in the vertical and horizontal direction over a plane tangent to the feet of the block model. The physical extents in the vertical and horizontal directions of the best fit half-cycle cosine functions to the vertical electric field component are required for use in the empirical relationship. These extents are equal to twice the distance between the half-power points on the two respective axes. Measurements of leakage fields from industrial RF heat sealers have shown that such fields are closely approximated by the best fit half-cycle cosine functions, as we have shown in an example. Numerical results have been presented to support the validity of the empirical relation. Experimental results supporting the results predicted by the empirical equation will be presented in a forthcoming paper. A highlight of this work is the considerably reduced whole-body-average SAR for near-field partial-body exposures as compared to the plane-wave irradiation conditions.

References

[1] H. G. Booker and P. C. Clemmow, "The concept of an angular spectrum of plane waves and its relation to that of polar diagram and aperture distribution," *Proc. Inst. Elec. Eng.*, (London), vol. 97, pt. III, pp. 11–17, Jan. 1950.

[2] I. Chatterjee, M. J. Hagmann, and O. P. Gandhi, "Electromagnetic energy deposition in an inhomogeneous block model of man for near-field irradiation conditions," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-28, pp. 1452–1459, 1980.

[3] M. J. Hagmann, O. P. Gandhi, and C. H. Durney, "Numerical calculations of electromagnetic energy deposition for a realistic model of man," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-27, pp. 804–809, 1979.

[4] O. P. Gandhi, E. L. Hunt, and J. A. D'Andrea, "Deposition of electromagnetic energy in animals and in models of man with and without grounding and reflector effects," *Radio Sci.*, vol. 12, no. 6(S), pp. 39–47, 1977.

[5] R. A. Tell and E. D. Mantiply, "Population exposure to VHF and UHF broadcast radiation in the United States," *Proc. IEEE*, vol. 68, pp. 6–12, 1980.

[6] K. H. Mild, "Occupational exposure to radio-frequency electromagnetic fields," *Proc. IEEE*, vol. 68, pp. 12–17, 1980.

[7] O. P. Gandhi, M. J. Hagmann, and J. A. D'Andrea, "Part-body and multibody effects on absorption of radio-frequency electromagnetic energy by animals and by models of man," *Radio Sci.*, vol. 14, no. 6(S), pp. 15–21,

[8] M. J. Hagmann, O. P. Gandhi, J. A. D'Andrea, and I. Chatterjee, "Head resonance: Numerical solutions and experimental results," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-27, pp. 809–813, 1979.

[9] C. H. Durney, M. F. Iskander, H. Massoudi, and C. C. Johnson, "An empirical formula for broadband SAR calculations of prolate spheroidal models of humans and animals,"*IEEE Trans. Microwave Theory Tech.*, vol. MTT-27, pp. 758–763, 1979.

An Easy Tunable Stepped Coupled Lines Filter

GISBERT SAULICH, MEMBER, IEEE

***Abstract*—A stripline bandpass filter setup consisting of two stepped coupled lines is presented, with special emphasis being given to practical realization. The theoretical design of the filter is based on the known synthesis of directional couplers and is outlined briefly. Practical setup of the filter, together with a simple tuning mechanism, is described in detail. Measurements performed show good agreement with theoretical results.**

I. Introduction

On microwave filters consisting of parallel-coupled lines, a lot of literature has been written [1]. By contrast, a line filter as shown in Fig. 1 will be described in the following which is composed of two symmetrical stepped coupled TEM-mode transmission lines. Both lines have the same characteristic impedance Z_0 and are both short circuited at one end.

II. Synthesis

In accordance with [2], the design of such filters may be based on the synthesis of directional couplers [3]. According to [2], the two design methods just differ in one point, namely the odd polynomials $U_N(x)$ to be calculated which have different curves and extremes.

For the squared magnitude of the complex transmittance $\underline{S}_{12}$ of the filter according to Fig. 1 there applies [2]

$$|\underline{S}_{12}(x)|^2 = 4\frac{U_N^2(x)}{\left(1+U_N^2(x)\right)^2}, \qquad x=\sin 2\pi\frac{l}{N\lambda} \tag{1}$$

where $U_N(x)$ is an odd real polynomial of Nth degree

$$U_N(x)=c_1\cdot x+c_3\cdot x^3+c_5\cdot x^5+\cdots+c_N\cdot x^N \tag{2}$$

whose basic curve for obtaining of bandpass behavior is shown in Fig. 2.

Calculation of this polynomial according to the curve in Fig. 2 constitutes the focal problem of the synthesis and can only be

Manuscript received March 2, 1981; revised June 29, 1981.

The author is with Deutsche Forschungs und Versuchanstalt für Luft and Raumfahrt, Hermann-Burgdorf Str. 48, 2110 Buchholz/Nordheide

0018-9480/81/1100-1238$00.75 ©1981 IEEE

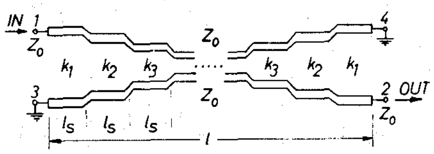

Fig. 1. Symmetrical multi-element TEM-mode coupled transmission line filter.

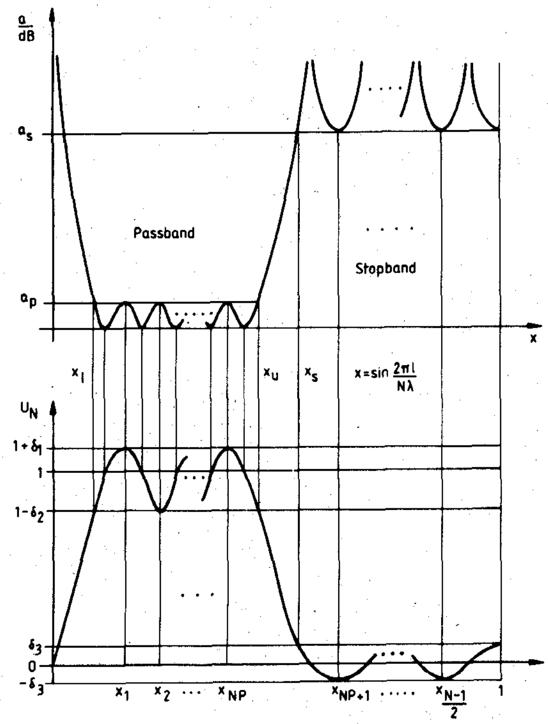

Fig. 2. Construction of the polynomial $U_N(x)$ to achieve bandpass behavior.

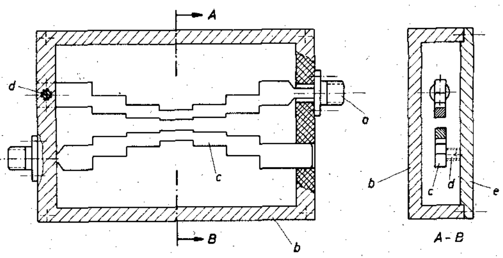

Fig. 3. Constructional set up of the filter based on rectangular stepped striplines.

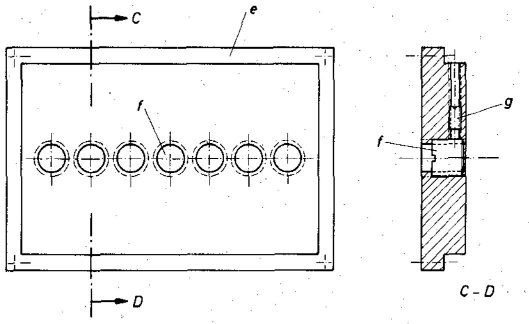

Fig. 4. Housing cover with tuning screws.

accomplished by the use of iteration procedures. Details of this procedure are found in [4]. When $U_N(x)$ is known, it is applied in the formulas indicated in [3] to obtain the input reflection coefficient Γ_{SIF} of the equivalent stepped impedance filter

$$|\Gamma_{SIF}|^2 = \frac{U_N^2(x)}{1+U_N^2(x)} \tag{3}$$

which is the basis for the well-known extracting process [3] for the characteristic impedances Z_i. Using the Z_i, the coupling coefficients $k_i = k_{N-i+1}$ of the steps of the coupled lines are subsequently calculated.

III. Realization of the Filter

Because of the structural identity of the filter according to Fig. 1 and a directional coupler made of coupled lines, extensive application of the directional coupler technology [3], [5] is feasible.

In the practical realization of the filter, tolerances and inaccuracies will in general not be able to be completely avoided, so that mechanisms for fine tuning of the attenuation characteristic will be indispensable. Hence the aim was to incorporate into the filter tuning elements which are as simple as possible and appropriately positioned.

Practical investigations have shown that the filter according to Fig. 1 is most favorably set up from rectangular shielded striplines, with tuning screws being arranged above the steps. This layout will be described in detail in the following.

The constructional set up of the filter [6] is depicted in Figs. 3 and 4. The filter is composed of the two stepped striplines c with rectangular cross section which, shielded in a metallic case b/e are electromagnetically coupled with each other, the dielectric being air. For better assembly of the lines c, the case b is provided with a screw cover e. At one end, the two striplines c are connected with coaxial RF connectors, while the other line end is placed in a groove in the case b with which it is electrically connected (short circuit) by means of the metallic set-screw d.

The two lines c are identical and have an arbitrarily odd number of steps (in the drawing, e.g., 7 steps), all steps being equal in length.

Spacing between the two lines varies from step to step, due to the different coupling coefficients and is symmetrical to the coupling path center and/or the intersection A–B. The characteristic impedance Z_0 of both lines is constantly equal to the characteristic impedance of the connectors (in general 50 Ω).

Manufacturing tolerances as well as the stepped structure of the striplines c may lead to sometimes considerable deviations from the theoretically calculated transmission characteristic. With the filter in Fig. 3 these difficulties may be overcome by attaching tuning screws f to the case cover e above the individual steps of the striplines c. By means of such screws variation is possible of the electromagnetic coupling of the two lines c within each step and with this of the whole filter characteristic. The tuning screws f are arrested each by the use of plastic set-screws g, in order to avoid detuning of the filter once it has been tuned.

Basic prerequisite for a successful tuning of the filter is an automatic scattering matrix test bench, by means of which the filter characteristic may be represented in the whole frequency range on a display and by means of which the influence of each individual tuning screw can be precisely observed. For the tuning itself it is important that with decreasing spacing between the lines c, the effect of the tuning screw increases; it is, however, not possible to supply a rule for the turning of the screws.

IV. Experimental Results

For checking the theoretical results, a filter was designed with $N=9$ steps, $NP=1$, maximally flat passband ($\delta_1 = \delta_2 = 0$ in Fig. 2) and a minimum stopband attenuation of $a_s = 50$ dB. The

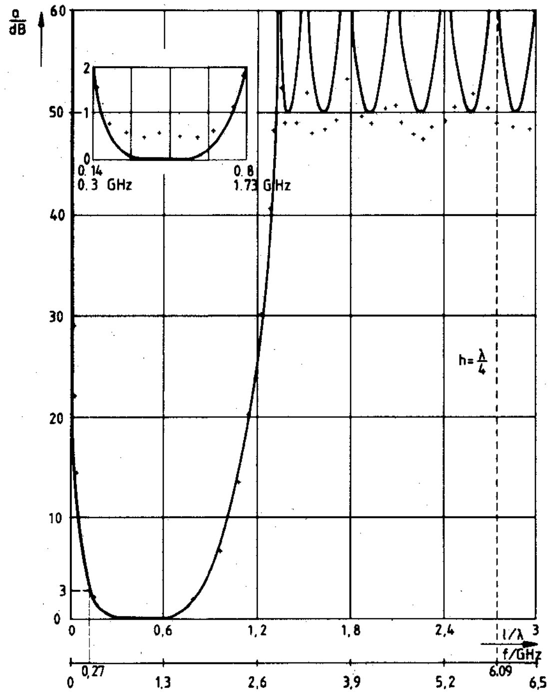

Fig. 5. Performance of the filter with maximally flat passband and a minimum stopband attenuation of $a_s = 50$ dB (— theoretical; + measured).

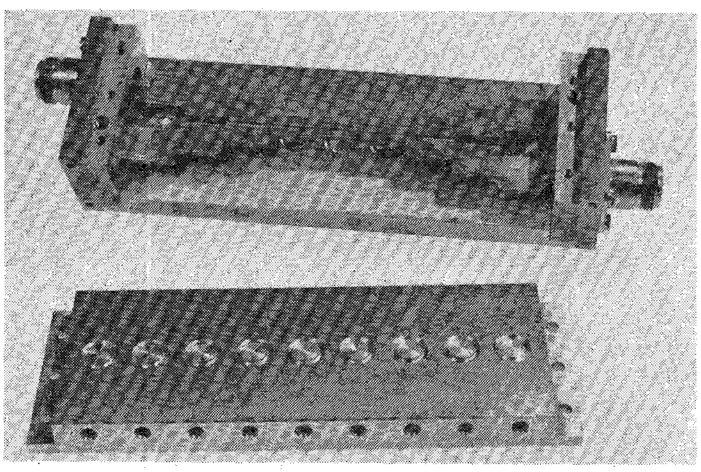

Fig. 6. Photo of the experimental filter with removed ground plane and cover with tuning screws.

maximum coupling coefficient in the center of the coupling path that could be realized for this filter was obtained to be $k_{max} = 0.82$. The theoretical attenuation curve is shown in Fig. 5.

The coupling path length $l = N.\ l_s$ was defined to be $l = 136$ mm, which corresponds to a lower limit frequency of the passband of $f_l = 270$ MHz at $a_p = 3$ dB. For the constructional design of the filter use was made of the relations and graphs for the even- and odd-mode impedances of rectangular shielded coupled lines in [3], [5].

Establishment of line thickness t and/or of ratio t/h (h = ground plane spacing) was made by the step with the smallest line cross section and/or the maximum coupling coefficient. The dimensions of this weakest point must still provide for an unproblematic manufacture of the striplines as well as for mechanical stability in the case. The appropriate value was found to be $t/h = 0.2$ and a ground plane spacing $h = 12.3$ mm, since the used 50-Ω connectors of the type UG-58 A/U have an external diameter of $D = h$. Fig. 6 shows the filter which was manufactured.

The striplines ($Z_0 = 50\ \Omega$) were made of bend-resistant aluminum with an accuracy of ± 0.01 mm. The spacing s between the two striplines in the center of the coupling path was set to be $s/h = 0.023$ by means of a feeler gauge.

Measurement of the filter was carried out on an automatic scattering matrix test bench as far as a frequency of 6.5 GHz. The first measurements yielding a minimum stopband attenuation of 24 dB showed indeed considerable deviations from theoretical results; these deviations could, however, be eliminated by means of the tuning screws. The values measured subsequently by means of a precision measuring line are plotted in Fig. 5. When the filter was first tested, the passband VSWR within the band-edge frequencies (3-dB band-edge points in Fig. 5) of 0.27 and 1.81 GHz reached peaks of 1.9, which is somewhat high. After tuning, the VSWR in the passband was improved to peaks of better than 1.34, respectively return loss of more than 16.75 dB.

V. Conclusion

The essential purpose of the physical investigations was to show that the effects of the line discontinuities on the transmission behavior of filters made of TEM-mode stepped coupled lines may be considerably reduced, if not eliminated, by means of simple tuning elements. This applies, however, only to filters consisting of massive striplines. It will have to be the subject of further investigations to study what kind of tuning elements are successfully suited for printed striplines.

References

[1] L. Young, *Microwave Filters Using Parallel Coupled Lines* Dedham, MA: Artech House, 1972.

[2] G. Saulich, "A stripline filter derived from directional couplers, in *Proc. 9th EuMC*, Brighton, England, (Sept. 17–20, 1979), pp. 381–385, 1979.

[3] L. Young *Parallel Coupled Lines and Directional Couplers*. Dedham, MA: Artech House, 1972.

[4] G. Saulich, "A new approach in the computation of ultra-high degree equi-ripple polynomials for 90°-coupler synthesis," *IEEE Trans. Microwave Theory and Tech.*, vol. MTT-29, Feb. 1981, pp. 132–135.

[5] G. L. Matthaei, L. Young, and E. M. T. Jones, *Microwave Filters, Impedance-Matching Networks, and Coupling Structures*. New York: McGraw-Hill 1964.

[6] German Patent Application No. 2 856 114.

Boundary Integral Equation Analysis of Transmission-Line Singularities

D. B. INGHAM, P. J. HEGGS, and M. MANZOOR

***Abstract*—The TEM line analysis of microstrips and coaxial lines generally involves boundary singularities which cause slow convergence of solutions computed by standard numerical techniques. In this study, the singularities occurring at the ends of the inner conductor in an unsymmetric closed microstrip containing a dielectric substrate, are treated by a modified boundary integral equation method. This method is shown to be successful in reducing the error due to the presence of the singularities.**

Manuscript received March 23, 1981; revised June 29, 1981. One of the authors (M. Manzoor) was supported by the Science Research Council.

D. B. Ingham and M. Manzoor are with the Department of Applied Mathematics, University of Leeds, Leeds LS2 9JT, England.

P. J. Heggs is with the Department of Chemical Engineering, University of Leeds, Leeds LS2 9JT, England.

0018-9480/81/1100-1240$00.75 ©1981 IEEE