# ADVANCES IN FIELD THEORETICAL INVESTIGATIONS ON DIELECTRIC IMAGE LINE ISOLATORS IN I-LINE TECHNIQUE

Dietmar Koether[1], Peter Waldow[2], Member IEEE, Birgit Neuhaus[2], Student Member IEEE
Dominique Schreurs[3], Senior Member IEEE and Adalbert Beyer[1], Fellow IEEE

[1] IMST GmbH, Carl-Friedrich-Gauss-Str. 2, 47475 Kamp-Lintfort, Germany
[2] Duisburg-Essen University, Bismarckstrasse 81, D-47048 Duisburg, Germany, email: a.beyer@uni-duisburg.de
[3] Katholieke Universiteit Leuven, Div. ESAT-TELEMIC, Kasteelpark Arenberg 10, B-3001 Heverlee, Belgium

***Abstract*** – Non-Radiative Dielectric Image Lines (NDGs) are waveguide structures in which a dielectric material serves to guide the electromagnetic waves. Among others, they could be accomplished as an I-guide or its modifications. This paper addresses various problems regarding to the design of a field displacement isolator in this technique. First, the electromagnetic field distribution in NDGs is shortly discussed. Subsequently, by the help of the Mode Matching (MM) technique, the calculation of isolator structures in I-line technique is performed. Thereafter, theoretical and experimental results, which show the capability of this device are introduced and intensively discussed.

***Index Terms*** – Fields in NDG-structures, I-Line Technique, Mode Matching Method, Dielectric Image Line Isolator, Magnetic Field Distribution, Scattering Parameters in Forward- and in Reverse Direction

## I. Introduction

Isolators are probably the most well-known nonreciprocal elements in the micro- and millimeter wave technology. In the ideal case, they have the characteristic to let through an undamped electromagnetic wave in the forward direction, and to close completely in the reverse direction. Thereby, no reflections of incident waves should raise in both directions. Isolators are used to match wave sources independently of the loading impedance and to protect the generator against reflected power. Also, it can be prevented, by their use in larger measurement setups, that standing waves are formed, overlaying with that signal, what can be measured and making an accurate determination of the scattering parameters of the device under test impossible.

Such a behaviour can be obtained by several isolator-principles, which are all caused by gyrotropic materials, usually dc magnetized ferrites. Among others, the Faraday effect or phase shifters with feed back can be used, in order to develop isolators. But these possibilities have the disadvantages that either cylindrical lines are required or the operating band is too small [1]. Furthermore, there are resonance- and field displacement isolators. In reality, a clear distinction of these two types is not always possible, because the maximum field displacement arises close to the gyromagnetic resonance. Anyway, this symptom leads to direction-controlled losses, if the waveguide structure is asymmetric. Therefore, also isolators show a transmission behavior, which corresponds to a resonance characteristic according to the principle of the field displacement.

As a starting point, a brief discussion of the electromagnetic field in NDG-structures will be explained.

## II. Fields In Non-Radiative Dielectric Guide Structures

The dielectric image lines are suggested for applications since 1952. Usually, they are threelateral open structures having a semicircular or a rectangular cross section. One common form of the dielectric image lines is the H-guide, which is concisely brought in between two, as ideal assumed, metallic plates (Fig. 1). Thus, it concerns of bilateral open dielectric image lines, in which different electromagnetic wave modes can propagate. This type of waveguides is well-understood and its calculation is described in numerous papers, e.g. in [2, 3]. In the following, some results will be presented, which depict the field distribution in H- as well as in I-guides. Those findings were obtained by using the MM technique [4], see subsection III.

Fig. 1 shows the distribution of the electromagnetic field of an H-guide for the $LSE_{11}$ mode. Those image lines using a quasi TEM wave form ($LSE_{10}$) are called as I-guides. In Fig. 2 the typical field distribution is represented.

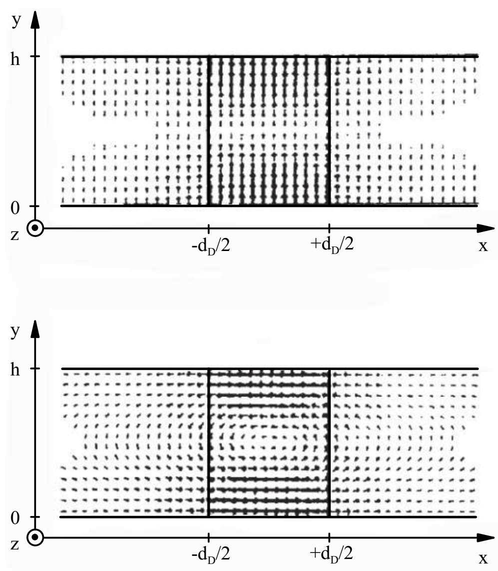


Fig. 1: Field distribution of the $LSE_{11}$ mode in a H-guide at a transversal plane ($f = 33$ GHz, $d_D = 4.0$ mm, $h = 5.0$ mm, $\varepsilon_r = 2.22$, $\tan\delta_\varepsilon = 2 \cdot 10^{-4}$, $\kappa = 62.5 \cdot 10^6 \frac{1}{\Omega\text{m}}$); Top: Electric Field; Bottom: Magnetic Field

As it is well-known, the transport of the electromagnetic wave in those guides takes mainly place in the dielectric material. The fields decrease in the outside space exponentially with the distance, thus this behavior describes also the concentration of the energy in the waveguide. For isotropic and gyrotropic materials the energy is directly proportional to the effective dielectric constant, which is given by the following relationship:

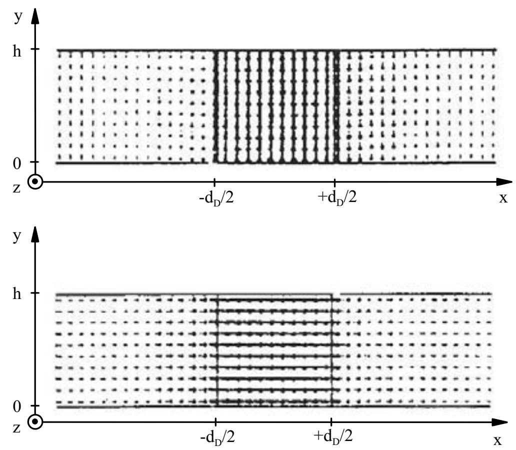


Fig. 2: Field distribution of the $LSE_{10}$ mode in an I-guide at a transversal plane ($f = 33$ GHz, $d_D = 3.5$ mm, $h = 3.5$ mm, $\varepsilon_r = 2.22$, $\tan\delta_\varepsilon = 2 \cdot 10^{-4}$, $\kappa = 62.5 \cdot 10^6 \frac{1}{\Omega\text{m}}$); Top: Electric Field; Bottom: Magnetic Field

$$\varepsilon_{\text{eff}} = \left(\frac{\beta}{k_0}\right)^2 \tag{1}$$

with $\beta$ the phase constant and $k_0 = \omega\sqrt{\varepsilon_0\mu_0}$ the wave number of vacuum.

If the effective dielectric constant is sufficiently large, usually much larger than unity, also the electromagnetic field will vanish in the outside space. For example, in an I-guide, operating in the Ka-band and having a width of 3 mm, for a distance of 5 mm, the field values are already decreased on approximately 10% against their original values. This behavior increases with rising frequency. Thus, also high integration densities with dielectric image lines can be attained.

A hindrance is, however that at discontinuities radiations arise, which lead to unwanted coupling within the circuit. Therefore, the NRD guides are frequently used. The problem can be solved for other, that is to say radiative image kinds of waveguides, however, by the employment of absorber materials in the appropriate places and by applying smooth transitions. If in the dielectric image line structure the dielectric road is replaced by a piece ferrite, so - in case of the

I-guide - the calculation of the field distribution can be performed by means of LSE modes, see Fig. 3.

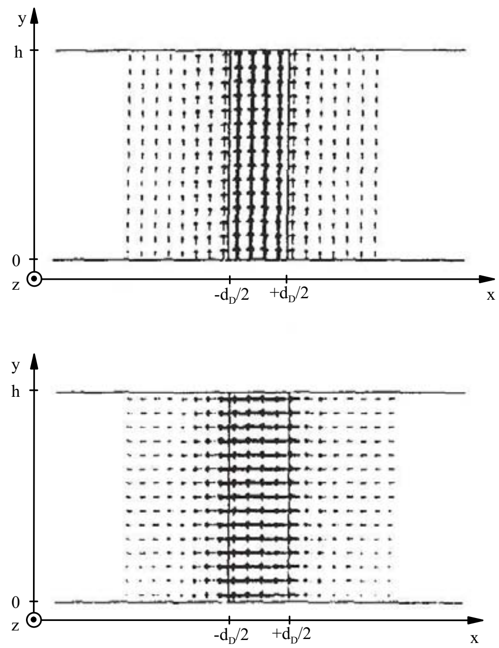


Fig. 3: Field distribution of the quasi $LSE_{10}$ mode in a I-guide using a TT2-111 ferrite piece at a transversal plane ($f = 33$ GHz, $H_0^i = 2,000\ \frac{\mathrm{kA}}{\mathrm{m}}$, $h = 3.556$ mm, $d_F = 1$ mm, $\varepsilon_r = 12.5$, $\tan\delta_\varepsilon = 2\cdot 10^{-4}$, $M_s = 397.9\frac{\mathrm{kA}}{\mathrm{m}}$, $g = 2.11$, $\tilde{\alpha} = 0.011$) Top: E-Field; Bottom: M-Field

It can be recognized that at such high values of the dc magnetization, the ferrite piece becomes isotropic. Thus, the field distribution is entirely analogue with that of an I-guide filled by an isotropic dielectric strip. The MM technique - which is widely used in analyzing waveguide structures with partly homogeneous material subregions - also allows the calculation of losses within this wave- guide, see Fig. 4.

The computation of the dielectric losses $\alpha_d$ on the I-guide is relatively simple: only the dielectric constant is need to be set complex. Following, also the phase constant $\beta$ yields as a complex value. The determination of metallic losses caused through the skin effect is performed via a perturbation calculation, which takes the surface impedance of the metallic plates into account. If one considers the gyromagnetic losses $\alpha_m$ of the ferrite, then the frequency response and the magnetic losses become frequency dependent, as represented in Fig 4. Here the dc magnetic field strength $H_0^i$ is selected in such a way that the gyromagnetic resonance can arise in a far frequency range outside the operating frequency regarded. Therefore, the magnetic losses ($\alpha_m$) are partially substantially larger at low values of dc magnetic field strength.

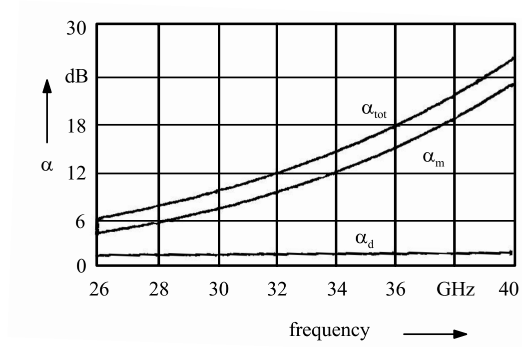


Fig. 4: Attenuation characteristic of an I-guide filled by ferrite for the $LSE_{10}$ mode; $\alpha_d$: dielectric attenuation, $\alpha_m$: gyromagnetic attenuation, $\alpha_{\mathrm{ges}}$: total attenuation. (for the data, see Fig. 3)

In the following an isolator is developed in I-line technique, whose substantial mechanism is based on the field displacement by dc magnetized ferrites. The direction-controlled absorption features are caused mainly by additional absorbers.

## III. Field Theoretical Analysis For An Isolator In I-Line Technique

The configuration in Fig. 5 shows an isolator, which is composed of a dielectric-, a ferrite- and an absorber material. The latter two areas are still separated from each other by a resistive foil with negligible thickness.

This structure is to be treated using the MM method [4], which is - as already mentioned - a

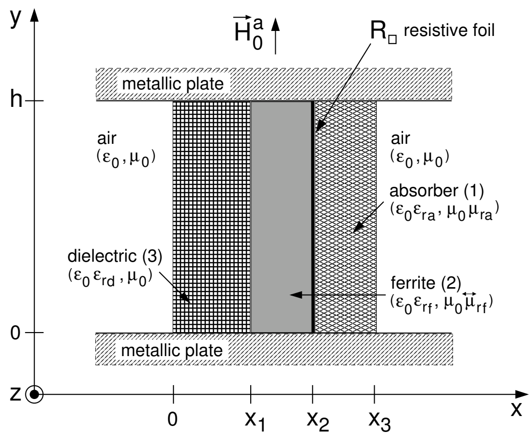


Fig. 5: Cross-section of an isolator in dielectric image line technique

very general-valid and a rigorous full-wave approach suitable for the processing of complex electromagnetic problems with partial homogeneous material subregions.

The necessary equations for matching the electromagnetic fields in the interfaces between two adjacent sub-regions (absorber (1) and ferrite (2)) [5] must also take into account the surface current, which flows in the resistance foil and is caused by the electromagnetic field.

It yields for the continuity of the electric field strength component $E_y$:

$$E_{y2} - E_{y1} = 0 \tag{2}$$

and for the effect of the surface current:

$$H_{z2} - H_{z1} = -S_{Fy} = -\frac{E_{y1}}{R_F} \tag{3}$$

with $R_F$ the surface resistance of the resistive foil and $S_F$ the surface current. Now, consider the right open region of the isolator in Fig. 5 which is filled with air and which is is extended to $x \to \infty$. Thus, the following expression for $LSE$-waves in the electromagnetic field may be found:

$$E_y = A \exp(-k_x(x - x_a)) \exp(-\gamma z) \tag{4}$$

$$H_x = \frac{-\gamma}{j\omega\mu_0} A \exp(-k_x(x - x_a)) \exp(-\gamma z) \tag{5}$$

$$H_z = \frac{+k_x}{j\omega\mu_0} A \exp(-k_x(x - x_a)) \exp(-\gamma z) \tag{6}$$

with the propagation constant $\gamma$, the co-ordinate $x_a$ of the interface between the layers absorber/air and the wave number $k_x$ in $x$-direction. The wave number $k_x$ is given by:

$$k_x^2 = -k_0^2 - \gamma^2. \tag{7}$$

with $k_0$ the wave number of vacuum given by: $k_0 = \omega\sqrt{\mu_0 \varepsilon_0}$.

The electromagnetic field within the left region of the isolator, which is also filled with air, can be represented similarly. Herein, the quantity $+k_x$ must be used instead of $-k_x$.

The ferrite filled region in Fig. 5 is described under the assumption, that - in case of the I-guide - no $y$-co-ordinate dependency of the field component exists. Furthermore, only the $E_y$-component of the magnetic field strength occurs. Hence, the following solutions of the Maxwell's equations can be obtained:

$$E_y = [\, A \sin(k_x(x - x_a)) + B \sin(k_x(x - x_b)) \,] \cdot \exp(-\gamma z) \tag{8}$$

$$\begin{aligned} H_x = \Bigg[ & A \left( \frac{+j\gamma}{\omega\mu_0\mu_{1\mathrm{eff}}} \sin(k_x(x - x_a)) + \frac{+k_x}{\omega\mu_0\mu_{2\mathrm{eff}}} \cos(k_x(x - x_a)) \right) \\ & + B \left( \frac{+j\gamma}{\omega\mu_0\mu_{1\mathrm{eff}}} \sin(k_x(x - x_b)) + \frac{+k_x}{\omega\mu_0\mu_{2\mathrm{eff}}} \cos(k_x(x - x_b)) \right) \Bigg] \exp(-\gamma z) \end{aligned} \tag{9}$$

$$\begin{aligned} H_z = \Bigg[ & A \left( \frac{-k_x}{j\omega\mu_0\mu_{1\mathrm{eff}}} \cos(k_x(x - x_a)) - \frac{j\gamma}{j\omega\mu_0\mu_{2\mathrm{eff}}} \sin(k_x(x - x_a)) \right) \\ & + B \left( -\frac{k_x}{j\omega\mu_0\mu_{1\mathrm{eff}}} \cos(k_x(x - x_b)) - \frac{j\gamma}{j\omega\mu_0\mu_{2\mathrm{eff}}} \sin(k_x(x - x_b)) \right) \Bigg] \exp(-\gamma z) \end{aligned} \tag{10}$$

with the wave number $k_x$ in $x$-direction

$$k_x^2 = \varepsilon_r \; \mu_{1\mathrm{eff}} \; k_0^2 + \gamma^2 \tag{11}$$

The quantities $\mu_{1\text{eff}}$ and $\mu_{2\text{eff}}$ are defined by

$$\mu_{1\text{eff}} = \frac{\mu_1^2 - \mu_2^2}{\mu_1} \qquad \mu_{2\text{eff}} = \frac{\mu_1^2 - \mu_2^2}{\mu_2} \tag{12}$$

and they are elements of the permeability tensor $\overleftrightarrow{\mu}_r$:

$$\overleftrightarrow{\mu}_r = \begin{bmatrix} \mu_1 & 0 & +\mathrm{j}\mu_2 \\ 0 & 1 & 0 \\ -\mathrm{j}\mu_2 & 0 & \mu_1 \end{bmatrix} \tag{13}$$

The field expressions for a subarea filled by an isotropic dielectric or an absorber material (see Fig. 5) are analogous to those (see Eqs. (8) - (11)) used for the ferrite region. Only the respective material constants $\varepsilon_r$, $\mu_{1\text{eff}} = \mu_r$ and $\mu_{2\text{eff}} \rightarrow \infty$ have to be applied. Since the permittivity and the permeability of these materials can be complex values, the wave number $k_x$ in $x$-direction, linked with these complex material characteristics, is a complex quantity, too. It should be mentioned that these conditions were used for calculating the results discussed in subsection II.

By using these field solutions, see Eqs. (4) - (13), for the different homogenous areas the unknown amplitude coefficient can be eliminated satisfying the continuity conditions of the field components given by the Eqs. (2) and (3). Subsequently, a system of homogeneous algebraic equations for the propagation constant $\gamma$ may be obtained. The solutions of this system are complex values caused by the electric parameters of the materials used.

## IV. Results and Discussion

In order to qualify the operation of an isolator, its properties in transmission and isolation direction should be determined. This is done via the computation of the propagation constant $\gamma$ for wave propagation in $+z$ (and $-z$) direction [6, 7]. The relationship of the attenuation constants $\alpha$ in forward and reverse direction is equal to the figure of merit. This statement is correct only if no power is transported by higher order wave modes. Otherwise, their excitation must be considered with the determination of the propagation properties of the device.
These higher order wave modes are bound more weakly to the line and therefore also less absorbed. That affects particularly the isolation behavior. Hence, the isolators are to be dimensioned in such a way that at the discontinuities only a small amount of higher order wave modes become excited. It is important to mention that it is not possible to guarantee the propagation of the fundamental mode only because of the high values of the permittivity of ferrite materials.

The isolator structure in Fig. 6 is a combined I-guide according to the longitudinal cross-section shown in Fig. 5, which uses the field displacement effect.

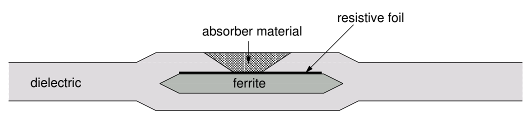


Fig. 6: Arrangement of an isolator. Dimensions of the ferrite: 6 cm x 1 mm x 3.55 mm. Type of the ferrite: TT2-111

For the isolator in Fig. 6 the computed magnitudes of the attenuation scattering parameters $S_{21}$ and $S_{12}$ are depicted in Fig. 7, whereas in Fig. 8 the magnetic field distribution in the x-z-plane is shown. It is visible in Fig. 8 that in the reverse direction near the resistive foil the electromagnetic field is strongly displaced.

A view of the experimental results represented in Fig. 9 shows an attenuation in forward direction of better than $-3.5$ dB and an attenuation in the reverse direction of better than $-17.5$ dB with a operating frequency band of 2 GHz and a center frequency of 29 GHz. It results in a relationship of 14 dB figure of merit and a relative operating frequency band of nearly 7%. The theoretically predicted result given in Fig. 7 is strongly overlaid from disturbances, but nevertheless, the tendency of the curves is agreeing. The disturbances result themselves on the one hand from the transition, which is still too abrupt, of the dielectric image line to the line with ferrite (jump of the dielectric constant of $\varepsilon_{rD} = 2.22$ on $\varepsilon_{rF} = 12.5$), and on the other hand, with the computation of the transmission characteristics of the isolator higher order wave modes are not yet considered. But they are excited at the transitions

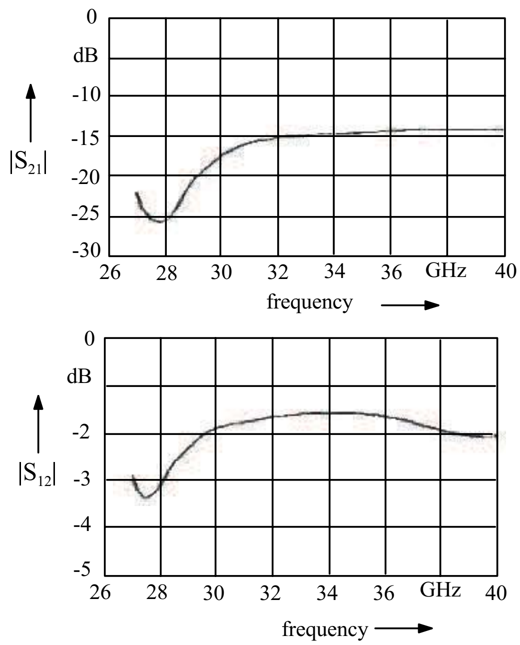


Fig. 7: Calculated magnitudes of the attenuation scattering parameters $S_{21}$ and $S_{12}$ of the isolator. Top: reverse attenuation Bottom: forward attenuation

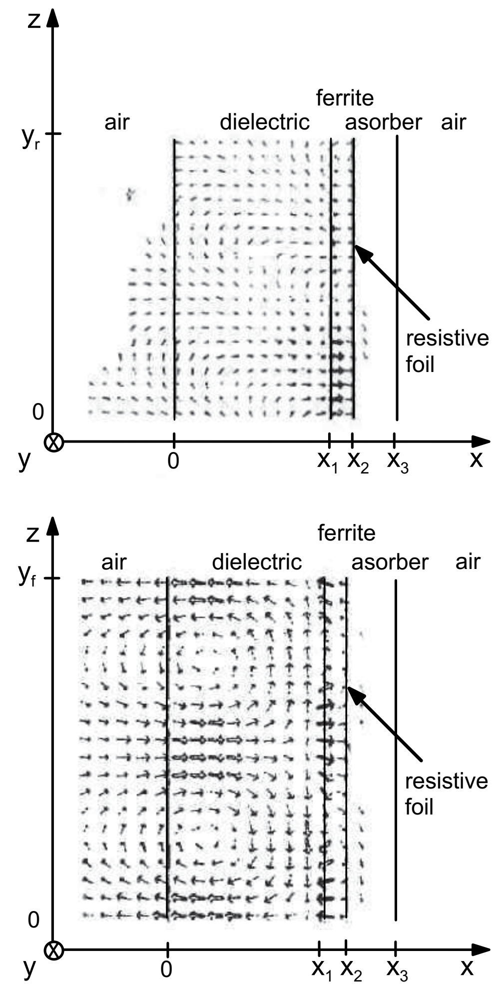


Fig. 8: Longitudinal distribution of the magnetic field strength in the x-z-plane over one wavelength. Top: reverse direction Bottom: forward direction

and, however, as already mentioned, more weakly bound to the line. Most remarkable are the strong oscillations of the transmission curves. Since the two transitions of dielectric image line to dielectric image line with ferrite (see Fig. 6) exhibit in each case quite high reflections, they form together a resonant line system. Because the I-line with ferrite possesses a highly effective dielectric constant, the phase constant grows thus fast with the frequency and the frequency spacing between the individual resonances becomes small.

## V. Conclusion

In the framework of this paper the dielectric image lines in I-guide technique were examined concerning their characteristics and usefulness for the fabrication of non-reciprocal devices. The I-guide is very suitable, because its technique permits both a good adjustment of the ferrite material and a simple production for the metallic plates.

With the help of the "Mode Matching" approach the possibility of realizing an isolator as a non-reciprocal device was investigated. Using the numerical results obtained, a strong field displacement effect could be observed. Hence, a field displacement isolator in I-guide technique was numerically calculated, subsequently, fabricated and investigated experimentally. The results of these investigations show the applicabil-

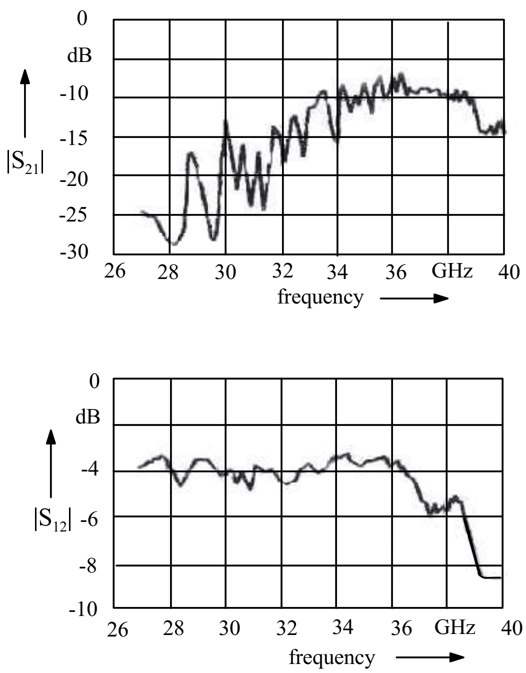


Fig. 9: Experimental determined magnitudes of the attenuation scattering parameters $S_{21}$ and $S_{12}$ of the isolator. Top: reverse attenuation Bottom: forward attenuation

ity of the method proposed.

In a next work, it should be examined, how the effects of the higher order wave modes are to be reduced. It is aimed at that the ferrite material without dielectric support can be inserted. With this measure, discontinuities can be avoided, and thus, a better field displacement can be achieved. With a fewer number of discontinuities also fewer reflections will arise, and this will render possible to improve the attenuation properties and the operation frequency bandwidth, as well.

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**Dr.-Ing. Dietmar Köther** Born in 1958 in Duisburg, Germany. He received the electrical engineering degree (MSc) from the University - GH - Duisburg in 1984. From 1984 to 1988 he worked at the Department of Electrical Engineering at the University-GH-Duisburg on the DFG project "Reciprocal and nonreciprocal image guide elements utilizing pre-magnetized ferrites". In 1989 he received the PhD degree.

From 1989 to 1992 he worked for ArguMens, responsible for the development of a CAD package and measurement programs. In 1991 the design study "40 / 80 GHz electronical MMIC circulators" started. Some activities were within the frame of Esprit II, Esprit III and BMBF DFE.

Since 1993 he is at the IMST where he was involved in the implementation of CPW elements into a CAD program. Further, non-standard measurement software for nonlinear characterization and active load pull has been developed. Since the beginning of 1995 he is head of the section „Simulation and Measurement Software" at the IMST. From 1996 till now, he is head of the section "RF Test Centre", which operates an ISO/IEC 17025 certified lab.

**Dr.-Ing. Peter Waldow** (IEEE member since 1984) received the Dipl.-Ing. degree in electrical engineering from the Gerhard-Mercator-University, Duisburg in 1982 and the Dr.-Ing. degree in 1986.

Since 1987 he was working on electromagnetic field theory in various industrial projects. He was co-founder in 1992 and is member of the Board of Directors of the Institute of Mobile and Satellite Telecommunications – IMST, Kamp-Lintfort, Germany.

Between 1999 and 2002 he was substitute of a Full Professor in the Engineering Faculty at the Gerhard-Mercator-University, Duisburg.

Currently, Dr. Waldow is adjunct Professor at the Department of Engineering Sciences, Institute of Communications Engineering, ATE at the University Duisburg-Essen, Location Duisburg.

**Dipl.-Ing. Birgit Neuhaus** was born in Oberhausen, Germany, in 1969. She received her diploma in Electrical Engineering from the Gerhard - Mercator-University of Duisburg, Germany, in 1998. She is currently working toward the Ph.D. degree at the Department of Electrical Engineering Sciences, at the University Duisburg-Essen, Location Duisburg. Her research interests are in modeling and simulation of microwave and optoelectronic devices. She is author and co-author of several papers, associate guest editor of scientific journals and workshop organizer. Mrs. Neuhaus is a member of the Association of German Engineers VDE and a Student Member of the IEEE.

**Dr. Ir. Dominique M. M.-P. Schreurs** (S'90-M'97-SM'02) received the M.Sc. degree in electronic engineering and the Ph.D. degree from the Katholieke Universiteit (K.U.) Leuven, Belgium, in 1992 and 1997, respectively.

She is currently a postdoctoral fellow of the fund for scientific research-Flanders and a visiting assistant professor at K.U.Leuven. She has been a visiting scientist at Agilent Technologies, ETHZ, and NIST. Her main research interest is the use of vectorial large-signal measurements for the characterization and modeling of non-linear microwave devices.

**Prof. Dr.-Ing. Adalbert Beyer** received his diploma in 1964 and the Dr.-Ing. (Ph.D.) degree in 1969, both in Electrical Engineer-ing. After occupying several industrial and academic positions, he joined the Duisburg University as Professor of Electrical Engineering and Millimeter-Wave Techniques. He is also foundation member of the “Sonder-forschungsbereich 254”. His areas of research interest are in the field theory, microwave- and millimeter-wave techniques and in the remote sensing. In 1987 he was a visiting professor at the University of Ottawa/ Canada. In 1990 he spent a time as visiting professor at the University of Texas at Austin/TX/USA. In 1996 he was visiting professor at the Technical University of Warsaw/ Poland. He is author and co-author of several books, patents and more than 300 technical articles. Professor Beyer is a Fellow of IEEE and a member of the IEEE MTT Symposia Technical Program Committes: MTT-S Education Committee, MTT-S Technical Committees MTT-13 and MTT-15. He is an Associate Editor of the *International Journal of RF and Microwave Computer-Aided Engineering* and a member of the editorial board of several scientific journals.