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ANALYSIS OF EXCITATIONS FOR A GROOVE GUIDE RESONATOR AT 10 GHz BY MEANS OF THE FDTD METHOD

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Abstract

Various excitations of a new groove guide resonator working in the X-band (8 GHz – 12 GHz) are investigated by means of numerical simulations. For the numerical simulations the Finite-Difference Time-Domain method is used. The groove guide resonator, modelled both with and without excitation structures, is discretised in space. The results in the time domain are then transformed into the frequency domain in order to obtain the resonance frequency spectrum. Comparison between simulations with and without excitations shows the effect of the excitations on the resonance frequency spectrum. The results are compared with those of previous analytical methods.

Keywords: Groove guide resonator, Finite-Difference Time-Domain method, Excitation, Millimeter waves.

1 Introduction

After Tischer [1] presented the groove guide as a low-loss alternative to classical waveguides, many studies on the groove guide evolved. Much work has focused on analytic solutions. For example, in [1] and [2] the conformal mapping method was applied, whereas in [3, 4, 5, 6] and [7] mode matching methods were proposed. Oliner and Lampariello [8] presented an improved solution for the mode matching method, while Fernyhough and Evans [9] focused on a full multimodal analysis. Due to the rapid development in computer technology, numerical methods became more popular, and their solutions have been presented in recent years.

For instance, in [10] and [11] the Finite Element Method (FEM) and in [12] the Finite-Difference Time-Domain method (FDTD) have been applied.

Interestingly, for all these studies, there is no investigation on excitations of the groove guide. As a means to excite the groove guide a so-called mode launcher has been proposed in the works of Griemsmann [13], Nakahara and Kurauchi [3] and of Liu and Yang [14]. However, this kind of excitation is not usable in resonator structures. Since the mode launcher is a transition from a rectangular waveguide to the groove guide, it requires that one end of the groove guide needs to be accessible. Therefore, in many applications different kind of excitations have to be used.

In the following, different kind of excitation structures are being presented and investigated. The excited structure is a semi-symmetrical groove guide resonator with both its ends electrically shorted. Since the groove guide resonator is an open structure, it offers several new applications. For instance, a dielectric sheet with known dimensions can be inserted easily into the groove guide. Due to the shift of the resonance frequency, its permittivity can be determined. Another application is to use the resonator as a distance meter. In this way, the distance between the two groove guide parts is adjustable. The distance defines the cutoff frequency of the guide and therefore the resonance frequencies of the resonator. For instance, decreasing the distance results in increased resonance frequencies.

2 The Semi-symmetrical Groove Guide Resonator

In this work, the used structure is based on the semi-symmetrical groove guide which has been discussed in [12] and [15]. It consists of a grooved plate and a plane plate. Both ends of the groove guide are shorted with metallic plates. A three-dimensional exploded view of the groove guide resonator is shown in Fig. 1. The resonator was designed to operate between 8 GHz and 12 GHz, i.e. in the X-band. Corresponding to the frequency range, the groove width is $w = 30$ mm and the groove depth is $d = 10$ mm. The plate distance h is 10 mm. The length t of the outer region was chosen to be 60 mm. This length is large enough, so that the evanescent electromagnetic fields are negligible at the outer edges. The length ℓ of the resonator was chosen to be 100 mm.

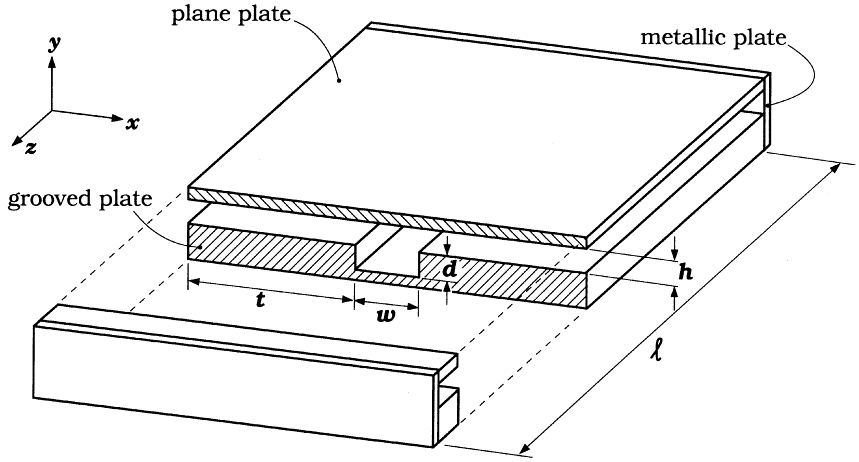


Figure 1: 3-D view of the groove guide resonator

In the following, the cutoff frequencies for the first $\mathrm{TE_{mn}}$- and $\mathrm{TM_{mn}}$-modes are determined, whereas index n indicates the field variation in x-direction and index m the field variation in y-direction. The determined values for the lower modes, using the method in [9], are listed in Table 1. Note that computing the cutoff frequency for the $\mathrm{TE_{11}}$-mode by the method of Oliner and Lampariello [8] gives the same value as computed with the method in [9].

Table 1: Determined cutoff frequencies f_c for the lower modes after Fernyhough and Evans [9]

$\mathrm{TE_{11}}$	:	7.79 GHz	$\mathrm{TM_{11}}$	:	8.78 GHz
$\mathrm{TE_{21}}$	:	9.55 GHz	$\mathrm{TM_{21}}$	:	14.50 GHz
$\mathrm{TE_{12}}$	:	12.80 GHz			

Within the frequency band of interest, there exist three propagating modes, namely the $\mathrm{TE_{11}}$, $\mathrm{TE_{21}}$ and $\mathrm{TM_{11}}$ modes. However, in Section 3, excitations are presented which are designed to excite only the lowest order $\mathrm{TE_{11}}$-mode. Therefore, the focus of this work is on resonance frequencies resulting from the $\mathrm{TE_{11}}$-mode.

3 Stub-, Loop- and Slot-Excitation

As an alternative to the mode launcher, three different kind of excitation structures are presented. Similiar to the commonly used coaxial-waveguide transitions are the stub and loop excitations as depicted in Figs. 2(a) and 2(b). The stub excitation is an electric probe (maximum E-field) and the loop excitation is a current loop (maximum H-field). The slot excitation works like a slot antenna radiating into the groove guide as shown in Fig. 2(c). It is a tapered transition from a rectangular waveguide to a narrow slot.

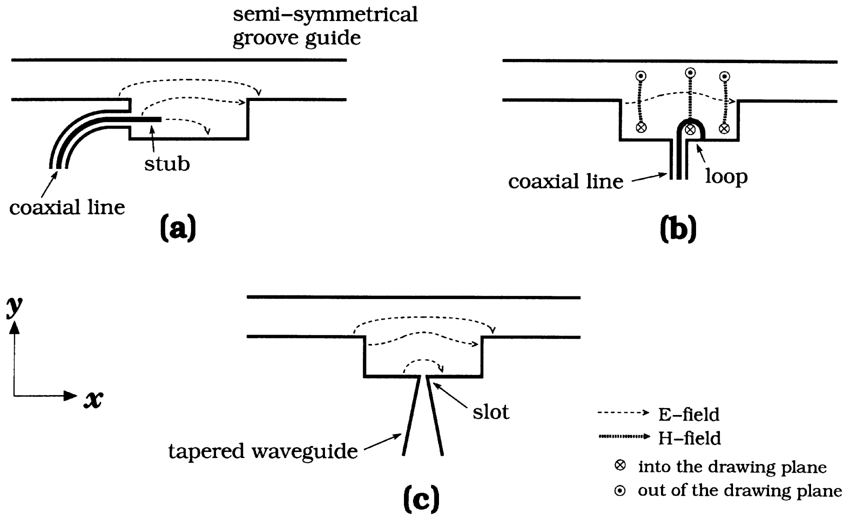


Figure 2: (a) Stub-, (b) Loop- and (c) Slot-Excitations for the Groove Guide depicted in the xy-plane with EM-fields of the lowest order TE-mode

For the TE_{11}-mode, the E- and H-fields are depicted in Fig. 2. The EM-field patterns for some modes in the groove guide have been presented in [3] and [13]. Based on those field patterns, excitation structures shown in Fig. 2 are proposed. Focus in this work is the excitation of the lowest order TE_{11}-mode. Hence the chosen positions of the excitations in Fig. 2.

4 Analytical Solution

In order to find the resonance frequencies for the TE_{11}-mode analytically, the so-called improved transverse resonance approach of Oliner and Lampariello [8] has been chosen. Comparison between the solution of their approach with their measurements showed very good agreement. First, the dispersion diagram for the semi-symmetrical groove guide has to be computed. The dispersion relation for the wavenumber $\beta = 2\pi/\lambda_z$ in propagation direction (z-direction) can be written as:

$$\cot\left(k_{x,1}\frac{w}{2}\right) = \left(\frac{h+d}{h}\right)^3 \cdot \left(\frac{\pi}{4}\right)^2 \cdot \frac{[1-(\frac{h}{h+d})^2]^2}{\cos^2\left(\frac{\pi h}{2(h+d)}\right)} \cdot \frac{k_{x,1}}{|k_{x,2}|}$$

$$+ \; 0.55 k_{x,1} \cdot \frac{2(h+d)}{\pi} \cdot \cot^2\left(\frac{\pi h}{2(h+d)}\right) \qquad (1)$$

where $k_{x,1}^2 = k^2 - (\pi/(h+d))^2 - \beta^2$ and $k_{x,2}^2 = -k^2 + (\pi/h)^2 + \beta^2$ are wavenumbers in the x-direction inside the groove region and in the outer region, respectively. The free-space wavenumber k is equal to $2\pi/\lambda$. The wavenumbers in the y-direction inside the groove region and in the outer region are $\pi/(h+d)$ and π/h, respectively. The resonance frequencies $f_{\mathrm{res,p}}$ for the $\mathrm{TE}_{11\mathrm{p}}$-modes are obtained by applying the resonance condition

$$\ell \; = \; \mathrm{p} \cdot \frac{\lambda_z}{2} \; = \; \mathrm{p} \cdot \frac{\pi}{\beta} \qquad \text{with } \mathrm{p} \in \mathbb{N} \qquad (2)$$

Resonance conditions for $\mathrm{TE}_{\mathrm{mnp}}$-modes with $\mathrm{m, n} \geq 2$ are not being considered. The wavenumber β versus frequency and the computed resonance frequencies are plotted into the dispersion diagram shown in Fig. 3. The resonance frequencies obtained from this diagram will be compared with the numerical simulation results.

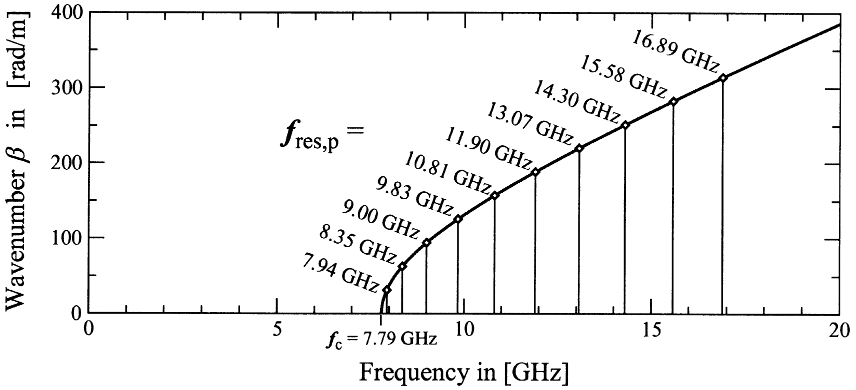


Figure 3: Dispersion diagram computed after Oliner and Lampariello [8] and resonance frequencies for the lowest order $\mathrm{TE}_{11\mathrm{p}}$-modes

5 Discretisation of the Structure in the FDTD-Domain

The FDTD method depends on the solution of Maxwell's equations directly in the time domain. Using a Taylor's expansion and discretising partial derivatives directly in time and spatial domain yield the well-known FDTD iterative equations [16]. Because of its rectangular shaped structure the groove guide resonator was discretised within the Cartesian coordinate system (x, y, z). In order to guarantee stability and a low numerical dispersion of the FDTD method, the discretisation in spatial domain must be sufficiently small.

The cell size was chosen to be $\Delta x = \Delta y = \Delta z = 0.25$ mm, which guarantees stability, a low numerical dispersion and a sufficient accurate discretisation of the excitation structures. The geometric dimensions and the cell size of the groove guide resonator require a total number of $620 \times 422 \times 126$ cells. Herein is included the absorbing boundary condition of a 10 cells thick perfectly matched layer (PML). Using floating point precision for the computation requires a total memory of about 2.7 GByte RAM. A time step of $\Delta t = 0.4815$ ps was chosen for the simulation. With a total of 32768 time steps this results in an observation time of 15.77 ns. After applying an off-line fast Fourier transform (FFT) this corresponds to a frequency resolution of about 60 MHz. For the FFT the Hanning window was used, since it gives a high frequency resolution and a low sidelobe ripple.

The source which is implemented in the algorithm is a modulated Gaussian-function, as described by Eq. (3). In order to fulfill causality, a time shift of $t_0 = 400$ ps is applied. Transformed into the frequency domain, the center frequency of maximum amplitude f_0 equals 10 GHz and the bandwidth B is 10 GHz, which covers the X-band.

$$g(t) = \exp\left(-B^2(t - t_0)^2\right) \cdot \sin(2\pi f_0(t - t_0)) \tag{3}$$

The source $g(t)$ is applied as an E-field $E(t, x_0, y_0, z_0)$ at one cell inside of the excitation structures. For instance, in Fig. 2(c) the source is centered inside the tapered waveguide and defines the E-field in x-direction. The observation point was placed symmetrically in the groove region, close to the plane plate.

6 FDTD Simulation Results

Figs. 4, 5(a) - (c) show the simulation results of the E_x-fields in the frequency domain, once at the source point and once at the observation point. In Fig. 4 the spectrum of the groove guide resonator without modelled excitation is plotted, i.e. the source is applied at one FDTD-cell directly inside the grooved region. The frequency spectra in Figs. 5(a) - (c) are for the groove guide resonator with its excitations placed as depicted in Fig. 2. Furthermore, after several iterative computations the optimum parameters for the excitations have been found as follows: The stub length was set to 5.0 mm, the loop area to 5×5 mm^2 and the slot width to 0.5 mm.

In each of the frequency plots the first eight resonance frequencies f_1 to f_8 are marked which correspond to the TE_{11p}-mode for $p = 1, 2, \ldots, 8$. Observed resonance frequencies between f_1 and f_8 which are not marked are due to self-resonances of the excitation structures. Several FDTD simulations have been performed, where the excitation structures vary in their physical dimensions. Those results show that the resonance frequencies, which are marked in the diagrams, do not change their values, whereas other resonances change in frequency while changing the excitation structure.

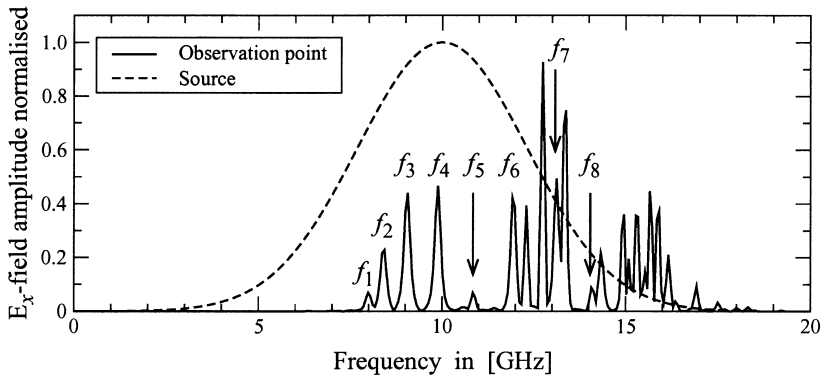
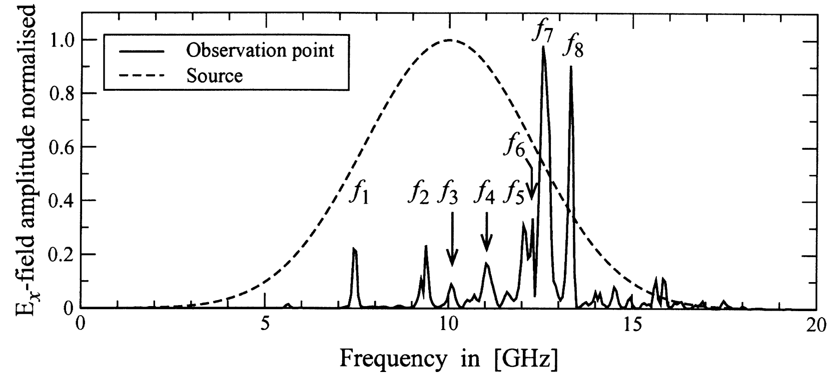
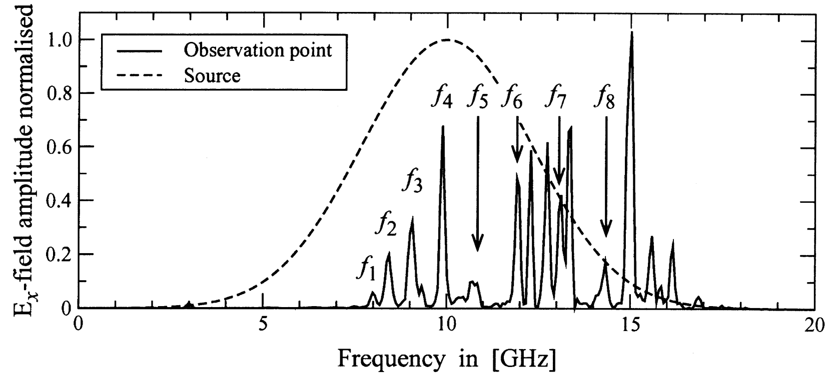


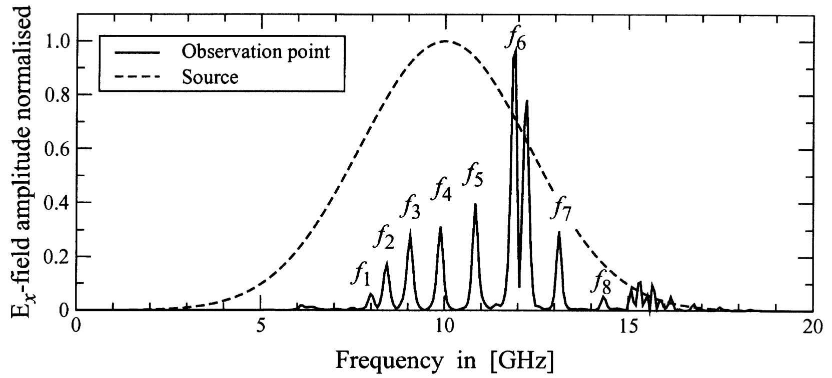
Figure 4: Excitation *not* modelled — E_x-fields of the source and at the observation point in frequency domain; off-line FFT with Hanning window



(a) Stub excitation



(b) Loop excitation



(c) Slot excitation

Figure 5: E_x-fields of the source and at the observation point in the frequency domain; applied off-line FFT with Hanning window

The numerically obtained resonance frequencies of the groove guide resonator with and without modelled excitation, together with the analytically obtained resonance frequencies are listed in Table 2.

Table 2: Via FDTD method computed resonance frequencies f_{p} of resonator without modelled excitation (None), with modelled excitations (Stub, Loop, Slot) and the analytically computed resonance frequencies (Analytic) after Oliner [8]

	$\mathrm{TE}_{11\mathrm{p}}$ resonances in GHz for $\mathrm{p} = 1, 2, \ldots, 8$							
	f_1	f_2	f_3	f_4	f_5	f_6	f_7	f_8
None	7.99	8.43	9.06	9.89	10.84	11.92	13.12	14.32
Stub	7.42	9.38	10.08	11.03	12.04	12.30	12.55	13.31
Loop	7.99	8.43	9.06	9.89	10.84	11.92	13.12	14.32
Slot	7.99	8.43	9.06	9.89	10.84	11.92	13.12	14.32
Analytic	7.94	8.35	9.00	9.83	10.81	11.90	13.07	14.30

Within a frequency resolution of 60 MHz, as calculated in Section 5, the numerical results for the loop and the slot excitation show the same values for the resonance frequencies. Also for the resonator without modelled excitation the same results have been obtained. Compared with the analytical solution, these resonance frequencies are about 20 MHz to 80 MHz higher than the resonance frequencies in the analytical solution.

The resonance frequencies of the groove guide resonator with stub excitation differ much compared to the analytical solution and other numerical simulation results. Inspecting additionally the E_z-field component reveals the following: For the loop and slot excitations the E_z-field component is of several magnitudes smaller than the E_x-field component. Therefore, with these excitations only the $\mathrm{TE}_{11\mathrm{p}}$-modes are excited. However, with the stub excitation, the E_z-field component is of the same magnitude and shows clearly dominant resonances as presented in Fig. 6. This indicates TM resonances. In addition to these resonances, the cutoff frequency of the TM_{11}-mode is marked in the diagram. The observed resonances f_1 to f_4 correspond to the $\mathrm{TM}_{11\mathrm{p}}$ modes, and their values are listed in Table 3.

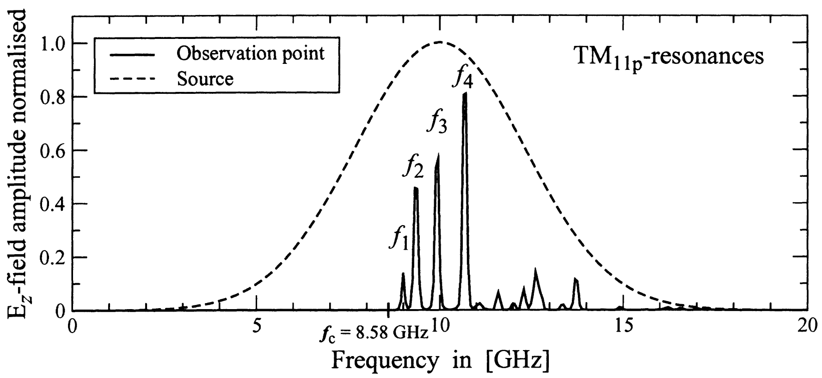


Figure 6: Stub excitation — E$_z$-field of the source and at the observation point in the frequency domain; applied off-line FFT with Hanning window

Table 3: Numerically computed TM$_{11p}$ resonance frequencies for the groove guide resonator with stub excitation

	TM$_{11p}$ resonances in GHz for p = 1, 2, 3, 4			
	f_1	f_2	f_3	f_4
Stub	9.00	9.32	9.95	10.71

7 Conclusion

In order to excite the lowest order TE mode of a groove guide resonator, best results are obtained by using loop or slot excitation. These results agree very good with the analytical solution. The loop excitation is applicable at lower frequencies around 10 GHz, where standard coaxial cables are used. The slot excitation is most convenient for resonators working at frequencies above 40 GHz, where waveguide constructions are common. The TE resonance spectrum with the lowest distortion is obtained with this kind of excitation. Regarding the loop and slot excitations, the modelling of the excitations seems not necessary in finding the resonance frequencies of the groove guide resonator. However, to observe effects of the excitation structure on unwanted resonance frequencies, like self-resonances of the excitation, modelling as accurate as possible is required. The example of the stub excitation shows the importance of modelling excitation structures. The frequency plot for TE resonances differs much from the corresponding frequency plots of the groove guide resonantor either with the other excitations or without modelled excitation. Consideration of all three E-field components shows that the stub excites TM modes.

Hence, with respect to costly fabrication, modelling excitations for the analysis gives information about whether a specific excitation will be applicable or not.

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