Dielectric Rod Waveguide Couplers as Harmonic Filters for Millimeter and Sub-Millimeter Wave Frequencies

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Abstract—The paper describes the design and the realization of bandpass filters for suppression of harmonic frequencies based on coupled dielectric rod waveguides at 75 GHz, 300 GHz and 450 GHz [1]. The theoretical values determined by Marcuțil’s method of approximation [2] were verified by broadband measurements on geometrically scaled coupler models at E-band frequencies. Afterwards, coupler filters were realized and experimentally characterized in the original frequency range at 300 GHz and 450 GHz. The filter setup was optimized with respect to low weight and compact dimensions for use on the mechanical field scanning unit of a modular vector field measurement system [3].

I. INTRODUCTION

A modular vector field measurement system (VFMS) for scanning spatially extended Gaussian beam fields at 150 GHz, 300 GHz and 450 GHz [3] was recently developed within the framework of a research project with contributions from the Technical Universities of Hamburg-Harburg and Darmstadt and from the University of Erlangen-Nuremberg called MEMSTIC (Multi Elements Multi Substrates Terahertz Integrated Circuits) [4]. The matter thereby is a novel quasioptical circuitry for efficient power combining of multiple solid-state components at 150 GHz and its harmonics. These elements are arranged in two-dimensional arrays and solely connected by a spatially extended quasioptical beam ([5],[6]). For controlling or optimizing the quasi-optical frequency multiplication, field measurements have to be done at the harmonics of interest. In this context, the presence of unwanted harmonics as well as the strong fundamental frequency has to be anticipated.

Consequently, bandpass filters at 300 GHz resp. 450 GHz to suppress the unwanted harmonics (in particular 450 GHz resp. 600 GHz) had to be developed and realized. Different concepts were evaluated. To integrate the harmonic filter on the mechanical field scanning unit of the vector field measurement system, the best suitable concept should fulfill the following requirements in equal measure:

- Low transmission losses in passband,
- high harmonic suppression in stopband (≥ 20 dB),
- required width of the passband n(150 GHz ±5) GHz, n ∈ {2;3} (as a result of the maximum LO bandwidth),
- low weight of the filter setup as well as
- compact dimensions.

A combination of coupled dielectric rod waveguides (DWGs) and metal hollow waveguides was chosen as base for the harmonic filter. At frequencies lower than the passband, it reflects signals by the cutoff of the hollow waveguide. Moreover, the frequency-dependency of the dielectric coupler separates the higher harmonics. Though other investigated concepts like quasioptical filters with a frequency selective surface on an (electrically) thick silicon substrate [7] also exhibit very good electrical properties, the coupler filter was preferred because of its low weight and the small filter setup. In addition, dielectric SMMW rod waveguides were used as main components of the VFMS anyway so the coupler filters do not cause any extra dielectric losses.

II. CALCULATION AND LAYOUT OF DIELECTRIC ROD WAVEGUIDE COUPLERS

A considerable part of the electromagnetic field is guided outside the (core) dielectric of the DWG which is also named "fiber" because of its tiny dimensions. Two parallel DWGs are therefore coupled, if the distance is low enough so that the electromagnetic wave is guided by both waveguides. This wave can formally be divided into two waves, namely the so-called even mode with the phase constant \( \beta_e \) and the so-called odd mode with the phase constant \( \beta_o \). If \( \beta_e \) and \( \beta_o \) are different, a coupling length \( L_0 \), the so-called zero-dB coupling length, exists as follows:

\[
(\beta_e - \beta_o) \cdot L_0 = \pi.
\]

This is illustrated by Fig. 1. The coupler is excited at port 1. After \( L_0 \), there is a complete power transfer from one guide to the other because of destructive interference at guide 1 and constructive interference at guide 2.

As the power of the signal is concentrating more and more in
the dielectric rod at increasing frequencies, $L_0$ is frequency-dependent. Its value increases strongly with the frequency.

Different parameters, like the axial propagation constant $k_z$ (of a single DWG), have to be calculated numerically to determine the value of $L_0$. We chose Marcatili’s method of approximation [2] for this purpose as it is rather simple to implement (e.g. in MATLAB) at a sufficient accuracy.

![Fig. 1. Superposition of even and odd mode on coupled dielectric rod waveguides [8]: The distributions of the E-field (y-axis) are rotated by 90° for better presentability](image)

According to Fig. 1, the output power of the coupler at port 4, $P_4(t)$, can be specified as a function of the coupled waveguide length $l$ as well as the input power $P_1(0)$ [9]:

$$P_4(t) = P_1(0) \cdot \sin^2 \left( \frac{\pi}{2} \frac{l}{L_0} \right)$$  \hspace{1cm} (2)

This is exemplified in Fig. 3 by coupling signals with two different frequencies $f_1$ and $f_2$ ($f_1 < f_2$). The signal power alternates periodically between both guides. To achieve a coupling of 0 dB at $f_1$, the belonging value of $L_0(f_1)$ is chosen as physical length of the coupler. At $f_2$, only a small fraction of the signal is coupled from guide 1 to guide 2, as $L_0(f_2) \gg L_0(f_1)$. The more $f_1$ and $f_2$ differ, the merrier is the filtering effect of the coupler.

By means of Eqn. (2), the theoretical insertion loss (without dielectric losses) was calculated for a filter based on a directional coupler with a passband at 150 GHz and harmonic suppression for $f \geq 300$ GHz. The appropriate dielectric fibers show the dimensions $a = 1.651$ mm and $b = 0.826$ mm. $L_0(f)$ was calculated for a distance between the fibers of $d = a/2$. The results are presented in Fig. 4. As $L_0$ is strictly increasing with the frequency, all higher harmonics are suppressed, contrary to filters based on resonant principles. Thereby, the stopband attenuation is also strictly increasing.

![Fig. 3. Periodic frequency-dependent power transfer at coupled dielectric waveguides](image)

![Fig. 4. Theoretical attenuation of a dielectric directional coupler according to Eqn. (2) for a 0 dB coupling at 150 GHz (without dielectric losses)](image)

### III. Realization and Experimental Characterization of Scaled Couplers at E-Band Frequencies

Beside the dimensioning of the couplers by theoretical calculations, an experimental optimization was performed at E-band frequencies (60–90 GHz).

The insertion loss was determined over frequency for different coupling lengths $l$ at a fixed distance $d = a/2$ between the fibers, which was also used for the calculations before. The length with the lowest insertion loss was considered as “zero-dB coupling length”. To extract the attenuation of the coupler, a continuous reference fiber was also measured in each case.
The couplers were geometrically scaled to ensure an identical $\alpha/\lambda_0$ (width of the dielectric fiber normalized to the wavelength), as the value of $\alpha/\lambda_0$ is critical with respect to $L_0$. The center frequency $f_{\text{scaled}}$ of the scaled passband (original frequency $f_{\text{orig}}$) can be determined by the widths $\alpha_{\text{scaled}}$ resp. $\alpha_{\text{orig}}$ of the belonging fibers as follows:

$$f_{\text{scaled}} = \frac{f_{\text{orig}} \cdot \alpha_{\text{scaled}}}{\alpha_{\text{orig}}} \quad (3)$$

In Fig. 6, the insertion loss of a coupler with the passband at 450 GHz was measured at a scaled center frequency of 81.3 GHz (450 GHz: 0.560 mm / 3.1 mm).

As the insertion loss of a scaled coupler at 300 GHz hardly differs from the results of the scaled coupler at 450 GHz, the results are not presented separately.

To prove the effectiveness of the filter at stopband frequencies, the E-band coupler has also be experimentally characterized at D-band frequencies (115–170 GHz).

IV. REALIZATION AND EXPERIMENTAL CHARACTERIZATION OF HARMONIC FILTERS AT 300 GHz AND 450 GHz

The results of the theoretical calculations as well as the experimental characterization of the scaled coupler models can directly be transferred to the design and the realization of harmonic filters at 300 GHz resp. 450 GHz.
Fig. 8 shows a filter unit at 300 GHz consisting of 2 cascaded couplers embedded in Styrodur. The small grooves were milled on a conventional milling machine with a micro milling cutter. Tests with a microscope equipped with a precise length measuring system showed that the actual widths of the grooves only differ $\leq 10 \mu m$ from the required nominal width of $a=0.864 \mu m$ at 300 GHz resp. $a=0.560 \mu m$ at 450 GHz, which was easily compensable by fine-tuning the coupling length. An effect on the properties of the filter was practically not detectable.

$$\text{Passband attenuation [dB]}$$

$$\text{Number of couplers}$$

\begin{tabular}{|c|c|c|}
\hline
Frequency [GHz] & Number of couplers & Passband attenuation [dB] \\
\hline
300 & 2 & 2.0 – 2.9 \\
450 & 3 & 3.5 – 4.5 \\
\hline
\end{tabular}

The measurement results at 300 GHz resp. 450 GHz are shown in Fig. 9 and Fig. 10. The maximum attenuation is $<2$ dB at 300 GHz and $<2.5$ dB compared to a continuous DWG of same length as the filter. The additional loss exhibits its maxima at both edges of the examined bandwidth and is $<1$ dB. Furthermore, the realized filters at 300 GHz and 450 GHz show quite compact dimensions: 140 mm x 22 mm x 20 mm, and a very low weight of $\approx 30$ g (filter without mount).

V. CONCLUSION

A combination of coupled dielectric rod waveguides and metal hollow waveguides was investigated as base for a band-pass filter for selecting desired harmonics of 150 GHz, namely 300 GHz or 450 GHz. The theoretical results determined by Marcatili’s method of approximation were verified by broadband measurements on geometrically scaled coupler models at E-band frequencies. Afterwards, coupler filters were realized and experimentally characterized in the original frequency range at 300 GHz and 450 GHz. The filter setup was optimized with respect to low weight and compact dimensions for use on the mechanical field scanning unit of a modular vector field measurement system.

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