Publication II

Tero Kiuru, Krista Dahlberg, Juha Mallat, Antti V. Räisänen, and Tapani Närhi. 2010. Noncontacting multiwaveguide-band backshort for millimeter wave applications. IEEE Microwave and Wireless Components Letters, volume 20, number 9, pages 483-485.

Noncontacting Multiwaveguide-Band Backshort for Millimeter Wave Applications

Tero Kiuru, Krista Dahlberg, Juha Mallat, Antti V. Räisänen, and Tapani Närhi

***Abstract*—In this letter a tunable, noncontacting and low loss waveguide backshort is presented. One backshort device is compatible with several standard waveguide sizes. The backshort is based on a quartz slab inserted in the E-plane of a rectangular waveguide. Simulation and measurement results for three standard millimeter waveguide bands are presented.**

***Index Terms*—Millimeter wave band, tunable backshort, waveguide backshort.**

I. Introduction

WAVEGUIDE backshorts are used at millimeter and submillimeter wavelengths in various applications. backshorts can be used, e.g., to tune the RF or LO impedance in mixers [1], as a variable load in noise parameter measurements [2] or to optimize the output power of cavity oscillators [3]. A waveguide backshort can be contacting, e.g., [4] or noncontacting [5], [6]. Contacting backshorts suffer from the inevitable wear of both the backshort and waveguide when the backshort is moved repeatedly. Noncontacting backshorts do not have this drawback, but as they are usually made of periodical low and high impedance sections, they exhibit resonance behavior. Furthermore, very tight machining tolerances are mandatory for both backshort designs in order to guarantee good performance, especially at sub-millimeter wavelengths.

A dielectric-based backshort was introduced and used at W-band in [7], [8] and used in a W-band double stub impedance tuner in [9]. The dielectric backshort is noncontacting, but does not consist of high-low impedance sections. It overcomes the problems of wear and resonance behavior and also partly the problem of tight machining tolerances, as the functionality of the backshort is not affected by slight dimension errors of the dielectric material. The dielectric backshort offers low losses and provides better tuning accuracy than the traditional backshorts. In this letter, the concept of the dielectric-based backshort is extended to a multiwaveguide-band compatible design. This means that the backshort is designed in a way that it can be used in several different sized waveguides with the same standard flange interface, which is not possible with other backshort designs. The backshort design is scalable to sub-millimeter wavelengths as the highest operation frequency is limited only by the thickness of the quartz slab and ultimately by the machining tolerances at very high frequencies (several THz with state-of-the-art milling machines). In order to validate the design, measurement results are provided for three different frequency bands, W (75–110 GHz), D (110–170 GHz) and G (140–220 GHz), respectively.

Manuscript received February 23, 2010; accepted May 20, 2010. Date of publication June 10, 2010; date of current version September 03, 2010. This work was supported in part by the ESA/ESTEC under Contract 22228/09/NL/GLC.

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Digital Object Identifier 10.1109/LMWC.2010.2051323

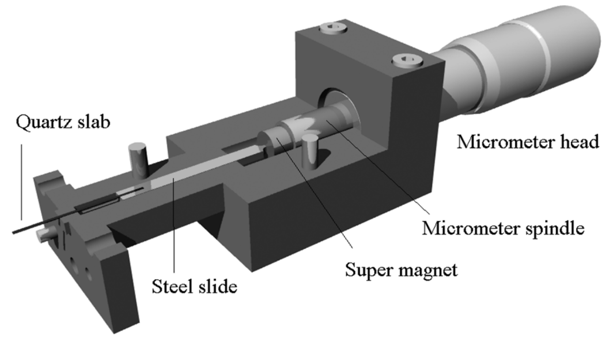

Fig. 1. Three-dimensional illustration of the backshort. Lower block of the structure is shown with micrometer head, super magnet, steel slide, and the quartz slab.

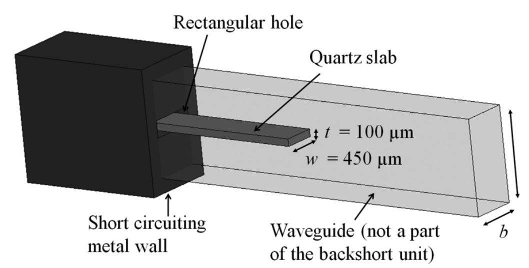

Fig. 2. Operation principle of the dielectric-based backshort.

II. Structure and Operation Principle

A three-dimensional model of the whole structure of the backshort is shown in Fig. 1. In the figure, the top half of the structure is removed for clarity. The backshort consist of two parts: mechanical and electrical. The mechanical part includes a micrometer head, super magnet and a steel slide on to which a quartz slab is attached with wax. The electrical part is simple: a metal plane for short circuiting the waveguide with a narrow rectangular hole through which the quartz slab is inserted into the waveguide. The material of the block is brass.

Fig. 2 illustrates the operation principle of the backshort. The short circuiting metal wall and the quartz slab are parts of the backshort unit and their dimensions remain constant in all measurements and simulations. The width and height of the waveguide, a and b change depending on the waveguide of the block, with which the backshort unit is used. A photograph of the backshort unit when connected to a lower split-waveguide block of a WR-5 waveguide is shown in Fig. 3.

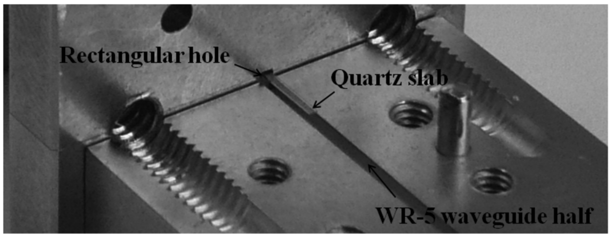

Fig. 3. Photograph of the backshort when it is next to a WR-5 waveguide split-block. The quartz slab is inserted through a rectangular hole into the waveguide.

The operation principle is straightforward. The metal plane with a rectangular hole presents a short circuit for the waveguide it is attached to. The quartz slab inserted to the waveguide through the rectangular hole changes the effective propagation constant of that part of the waveguide and thus the reflection coefficient phase seen from the other end of the waveguide, while the magnitude of the reflection coefficient stays close to unity. The width of the rectangular hole is an important parameter of the backshort, as it determines the highest operation frequency of the backshort. The cutoff frequency of the rectangular hole with some quartz filling must be above the TE_{10} mode operation frequency of the waveguide with which it is used. If the rectangular hole is not parallel with the E-field a mode conversion from TE_{10} mode to TE_{01} is possible and in this case the height as well as the width of the rectangular hole should be dimensioned to have the cutoff frequency above the operation frequency of the waveguide. The width of the rectangular hole is the thickness of the quartz plus a provision for the machining tolerances. In the backshort used for the measurements, the dimensions of the quartz slab are: thickness, $t = 100\ \mu\mathrm{m}$ and width, $w = 450\ \mu\mathrm{m}$. The dimensions of the rectangular hole are: width, $w = 230\ \mu\mathrm{m}$ and height, $h = 700\ \mu\mathrm{m}$. As a general rule, the thinner the quartz and the better the machining tolerances, the higher frequencies can be reached. This allows the straightforward scaling of the backshort design up in frequency as thinner quartz and smaller rectangular hole widths can be easily realized.

III. Measurement and Simulation Setup

W-band measurements were done with an HP 8510 Network analyzer. A two-port thru-reflect-line (TRL) calibration was performed before the measurements using an HP WR-10 Calibration Kit W1164A. D- and G-band measurements were done with an Agilent PNA Millimeter-Wave Network Analyser with Oleson V06VNA2-T/R-A and V05VNA2-T/R-A extension units for the D- and G-band, respectively. A two-port TRL-calibration was performed before the measurements with Oleson WR06 and WR05 Waveguide Calibration Kits for D- and G-bands, respectively. Even though the two-port calibration was used, the measurement results shown below are for the port where the backshort unit was attached. In all measurements the quartz slab was moved 8 mm inside the waveguide with 0.5-mm steps. The reference plane in the measurements is the backshort shorting plane, i.e., the plane where the quartz slab comes out from the rectangular hole. All simulations in this work have been done with the Ansoft's High Frequency Structure Simulator (HFSS) full wave simulator. In all simulations,

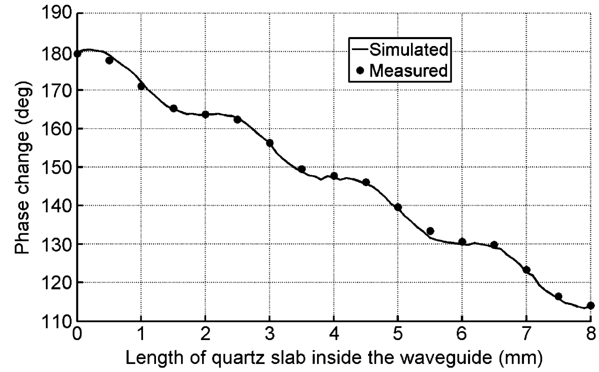

Fig. 4. Reflection coefficient phase change of the backshort as a function of the quartz slab length in the waveguide. Waveguide is a standard WR-10 (width $\mathrm{a} = 2.54\ \mathrm{mm}$ and height $\mathrm{b} = 1.27\ \mathrm{mm}$) and frequency is 92 GHz.

the material parameters used are the following: for the quartz slab, the loss tangent of $\tan\delta = 0.001$ and dielectric constant of $\varepsilon_r = 3.8$ are used. The metal used for the backshort shorting plane is brass, with conductivity $\sigma = 1.5 \times 10^7\ \mathrm{S/m}$ and the metal used for all the waveguides is gold, with conductivity $\sigma = 4.1 \times 10^7$. A surface roughness of 0.2 $\mu\mathrm{m}$ was used for all metal surfaces.

IV. Results

The simulated and measured reflection coefficient phase change as a function of the quartz slab length in the waveguide at the center of the frequency bands (92 GHz for W-band, 140 GHz for D-band and 180 GHz for G-band) is shown in Figs. 4–6. The measured phase change in different sized waveguides can be accurately predicted by the Ansoft's HFSS. It can be seen that the phase does not change linearly as a function of the quartz slab length in the waveguide. This is caused by the combination of the main reflection from the backshort shorting plane and the small reflection from the discontinuity of the empty waveguide and the waveguide with the quartz slab. The deviation from linear behaviour is periodical, with a period of exactly half of the simulated wavelength in the waveguide with the quartz slab. For 92, 140, and 180 GHz the simulated half wavelengths for the waveguides with the quartz slab are 2.026, 1.257, and 0.905 mm, respectively.

The losses for the backshort unit are very low and are caused by the metal wall reflection and quartz slab losses. This is illustrated in Fig. 7, where the measured return loss at the center frequencies of the W-, D- and G-bands is shown as a function of the quartz slab length inserted in the waveguide. The loss is less than 0.25 dB at D- and G-band and less than 0.05 dB at W-band. The fact that the average loss is larger for the D-band than for the G-band indicates a small measurement error as losses should increase with frequency. One possible cause might be that precision waveguides were available only for W- and G-band but not for D-band at the time of measurement. This can also be the reason for the phase deviation in the D-band shown in Fig. 5.

A popular figure of merit for backshorts is the maximum reflection coefficient or the corresponding voltage standing wave ratio (VSWR). In our case the maximum reflection coefficient is larger than 0.972 $(\mathrm{VSWR} = 70)$ at the center frequencies of D- and G-band, and larger than 0.988 $(\mathrm{VSWR} = 165)$ at the center frequency of W-band.

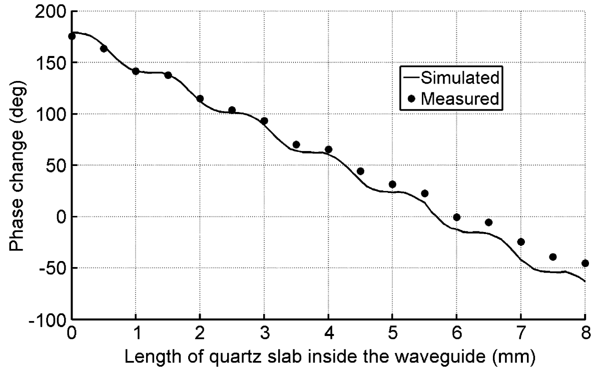

Fig. 5. Reflection coefficient phase change of the backshort as a function of the quartz slab length in the waveguide. Waveguide is a standard WR-6 (width $a = 1.651$ mm and height $b = 0.8255$ mm) and frequency is 140 GHz.

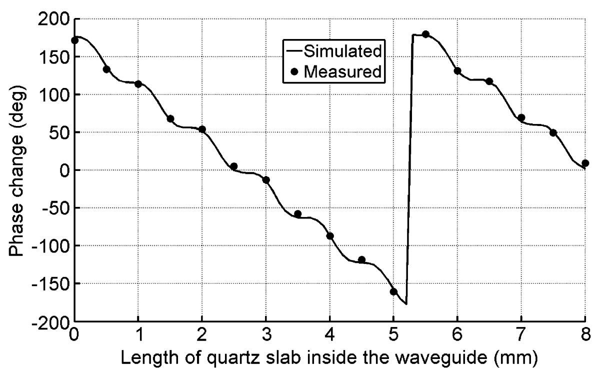

Fig. 6. Reflection coefficient phase change of the backshort as a function of the quartz slab length in the waveguide. Waveguide is a standard WR-5(width $a = 1.3$ mm and height $b = 0.65$ mm) and frequency is 180 GHz.

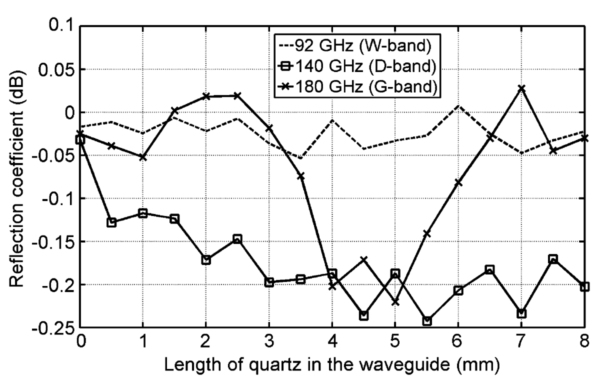

Fig. 7. Measured reflection coefficient (dB) as a function of the quartz slab length in the waveguide at the center frequencies of the W-, D- and G-band.

V. Advantages of the Backshort

Major advantages of the backshort presented in this work are the following. Low loss, simple design without very tight machining tolerances characteristic to traditional backshorts, no contact with the waveguide walls, no resonance behaviour, broadband operation over several waveguide bands, scalability to sub-millimeter wavelengths and very accurate tuning. To give an example of the last advantage, we will examine the backshort phase response at W-band more closely. The total phase change for the insertion of quartz from zero to 8 mm is 66° at 92 GHz, corresponding to an average phase change of $0.0825°/10\ \mu\text{m}$. In comparison with a traditional backshort, this phase change would be $0.847°/10\ \mu\text{m}$. On the other hand, a disadvantage of the backshort is the longer waveguide length it requires and the corresponding increase in losses. As an example, at 180 GHz, the reflection phase of a traditional backshort changes between 0° to 360° with about 1.1-mm movement of the micrometer spindle. In our case, where only the quartz slab is moving in the waveguide, the 0° to 360° phase change is obtained with 5.5-mm movement of the micrometer spindle and thus a 4.4 mm longer waveguide section is needed. The extra loss caused by this 4.4-mm waveguide section depends on the operation frequency and on the quality of the waveguide and is estimated to be around 0.1–0.2 dB at 180 GHz for a typical WR-5 waveguide.

VI. Conclusions

In this letter, we have presented a broadband, noncontacting multiwaveguide-band backshort. One backshort device is compatible with several standard waveguide sizes, which is not the case with other backshort designs. To the authors' knowledge, this is the first time that the same backshort unit is used with different waveguide sizes. Simulation and measurement results are given for the operation at three waveguide frequency bands. The backshort has low losses and avoids the disadvantages of traditional backshorts, like wear, resonant behaviour and tight machining tolerances. The backshort is suitable for millimeter wave applications, especially in situations where very low losses and accurate tuning are needed.

Acknowledgment

The authors wish to thank Dr. V. Möttönen for useful advice on the topic. E. Kahra is acknowledged for the mechanical fabrication of the tuner.

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