



HAL
open science

Six-Port Reflectometer in WR15 Metallic Waveguide for Free-Space Sensing Applications

Kamel Haddadi, Christophe Loyez, Laurent Clavier, Denis Pomorski, Simon Lallemand

► **To cite this version:**

Kamel Haddadi, Christophe Loyez, Laurent Clavier, Denis Pomorski, Simon Lallemand. Six-Port Reflectometer in WR15 Metallic Waveguide for Free-Space Sensing Applications. 2018 IEEE Topical Conference on Wireless Sensors and Sensor Networks (WiSNet 2018), Jan 2018, Anaheim, United States. hal-02013933

HAL Id: hal-02013933

<https://hal.science/hal-02013933>

Submitted on 11 Feb 2019

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

Six-Port Reflectometer in WR15 Metallic Waveguide for Free-Space Sensing Applications

¹Kamel Haddadi, ¹Christophe Loyez, ¹Laurent Clavier, ²Denis Pomorski and ³Simon Lallemand

¹Univ. Lille, CNRS, UMR 8520 - IEMN, F-59000 Lille, France

²Univ. Lille, CNRS, UMR 9189 – CRISAL, F-59000 Lille, France

³Groupe Segula Technologies, Valenciennes, France

kamel.haddadi@iemn.univ-lille1.fr

Abstract — This work describes the design, fabrication and measurements of a six-port reflectometer in metallic waveguide technology for operation around 60 GHz. The system integration is based on WR15 building blocks. An in-situ linearization of the detectors associated to a vector calibration procedure is provided to determine the calibrated IQ components from the measured voltages. Near-field free-space distance measurements from contact to stand-off distance of two free-space wavelengths are shown to validate the technique proposed.

Index Terms — Six-port, reflectometer, IQ demodulation, millimeter-wave, distance measurement,

I. INTRODUCTION

The six-port technique has been introduced in the 1970s as a simple technique for measuring power and reflection coefficient in the microwave regime [1]. Since then, a variety of six-port systems have been exemplarily demonstrated in metallic guide, substrate integrated waveguide (SIW), planar and monolithic forms [2]-[8]. Each technology presents own advantages and drawbacks in terms of circuit size, power consumption, immunity to temperature/hygrometry variations, fabrication facility, system integration, measurement performance and cost [8]. Therefore, the choice of the technology is mainly driven by the requirements of the targeted application.

This work presents a fully WR15 metallic waveguide six-port reflectometer operating at 60 GHz for near-field sensing applications, i.e. near-field high precision distance measurement. Unlike planar technologies systems, waveguides are highly shielded to provide isolation between nearby signals. As they rely on air as a dielectric, the technology reduces the need for consistency in the dielectric material and presents better immunity to environmental variations. Furthermore, the building blocks of the six-port circuit can be easily connected each other as they are inherently matched. As the size is directly related to the operation wavelength, millimeter-wave frequency operation is preferred to reduce the circuit size.

II. SIX-PORT IQ DEMODULATOR

This section describes the design, fabrication and test of the six-port IQ demodulator. The proposed architecture and picture of the fabricated system are given in Fig. 1.

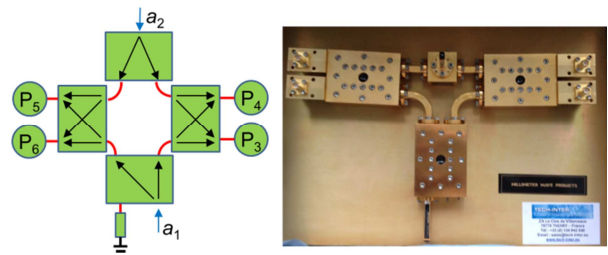


Fig. 1. (a) Structure of the six-port IQ demodulator. (b) Photograph of the WR15 waveguide six-port IQ demodulator.

The circuit is implemented using three 90° hybrids with 20 dB isolation and 6 % bandwidth around 60 GHz, a four port hybrid tee with one arm connected to a match termination for basic power splitting and four power detectors with typical video sensitivity of 500 mV/mW and tangential sensitivity of -50 dBm. Interconnecting bends and twists are used for system integration. The reference millimeter-wave signal a_1 [fig. 1(a)] can be provided by a miniature high stability phase-locked source Mi-WAVE™ 957 ($P_{LO} = 11$ dBm) or a frequency synthesizer Keysight™ E8257D.

The first step concerns the linearization of the electrical response of the power detectors to correct deviation from quadratic response. For this experiment, the RF port (signal a_2) of the six-port demodulator is connected to a match termination to make the electrical response depending only of the LO source signal a_1 . We present in Fig. 2 the detected voltages V_1 to V_4 measured for a source power varying from 10 μ W to 10 mW at 60 GHz.

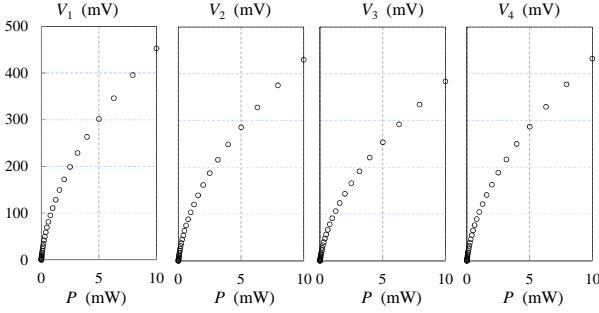


Fig. 2. Detected voltages as a function of the input millimeter-wave LO power – $F = 60$ GHz.

From Fig. 2, the linearity is degraded by distortions. The linearization procedure consists to interpolate the measured data using a polynomial function. In this study, a 5th order polynomial is used. As an example, the interpolation model for the voltage V_1 is given by

$$P_1 \text{ (mW)} = -1.43 \times 10^{-13} V_1^5 + 1.66 \times 10^{-10} V_1^4 - 8.04 \times 10^{-8} V_1^3 + 5.98 \times 10^{-5} V_1^2 + 4.02 \times 10^{-3} V_1 + 1.36 \times 10^{-2}.$$

The next step consists of verifying the performance in mixing mode. In this configuration, the millimeter-wave signal a_2 with amplitude A_{RF} is combined with the signal a_1 with amplitude A_{LO} . The theoretical powers P_3 to P_6 are given by

$$P_3 = |0.5(a_2 + a_1)|^2 \quad (1)$$

$$P_4 = |0.5(a_2 - ja_1)|^2 \quad (2)$$

$$P_5 = |0.5(a_2 - a_1)|^2 \quad (3)$$

$$P_6 = |0.5(a_2 + ja_1)|^2 \quad (4)$$

The 60 GHz LO and RF input signals are both obtained by the synthesizer using a power splitter. The source power is set to 11 dBm. The RF signal amplitude A_{RF} and relative phase-shift $\Delta\Phi$ are respectively adjusted with precise WR15 waveguide variable attenuator (MI-WAVE 510V/385) and phase-shifter (MI-WAVE 528V/385) as shown in Fig. 3. The IQ components are defined as

$$I = A_{RF} \cos(\Delta\Phi) \sim P_3 - P_5 \quad (5)$$

$$Q = A_{RF} \sin(\Delta\Phi) \sim P_6 - P_4 \quad (6)$$

A spatial (related to the spatial phase-shift $\Delta\Phi$) Fourier analysis is considered to correct the general forms given by (5) and (6) into the models (7) and (8) that encompasses mismatching and non-linear effects [9].

$$P_3 - P_5 = y_0 + y_1 I + y_2 Q + y_3 I^2 + y_4 Q^2 + y_5 (I^2 - 3IQ^2) + y_5 (Q^2 - 3I^2Q) \quad (7)$$

$$P_6 - P_4 = y'_0 + y'_1 I + y'_2 Q + y'_3 I^2 + y'_4 Q^2 + y'_5 (I^2 - 3IQ^2) + y'_5 (Q^2 - 3I^2Q) \quad (8)$$

These equations rely the powers to polynomial combinations of I and Q through eight real calibration

constants y_i and y'_i . More information about the model construction is given in [9].

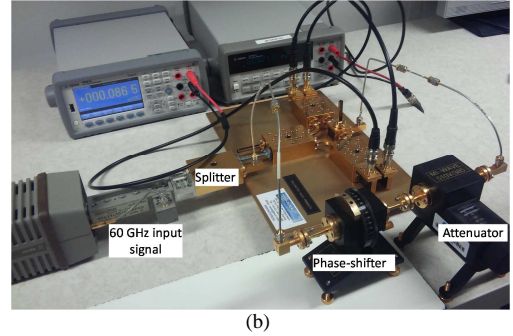
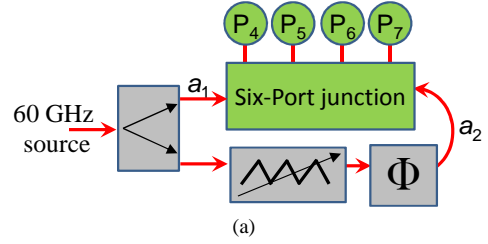


Fig. 3. Experimental test bench arrangement for IQ measurements.

The calibration coefficients y_i and y'_i are determined by fitting the measured powers to the models (7) and (8). For comparison purposes, the calibration constants are determined for the 1st ($y_3 = y_4$ and $y_5 = y_6 = y_7 = 0$), the 2nd ($y_6 = y_7 = 0$) and the 3rd orders. Table I reports the parameters obtained for $P_3 - P_5$. The 3D fitting according to the 3rd order model is also illustrated in Fig. 4. These results show that the spatial non-linearity effect has relatively low impact. However, metrological applications that require a high degree of accuracy can benefit from a 3rd order model that achieves a determination coefficient of nearly 1 computed on 259 points. Equivalent result has been found for $P_6 - P_4$. The calibration has been also validated in the frequency band 55-75 GHz.

TABLE I. CALIBRATION COEFFICIENTS ESTABLISHED FOR $P_3 - P_5 - F=60$ GHz.

Coefficient	Parameter	Order 1	Order 2	Order 3
Y_0	1	-0.2457	-0.2457	-0.2457
y_1	I	0.6575	0.6592	0.6593
y_2	Q	-1.1466	-1.1466	-1.1466
y_3	I^2	-0.0102	-0.0504	-0.0504
y_4	Q^2		0.0321	0.0321
y_5	IQ	—	-0.0152	-0.0152
y_6	$I^3 - 3IQ^2$		—	-0.0001
y_7	$Q^3 - 3I^2Q$	—	—	-0.0128
r^2		99.80%	99.88%	99.89%

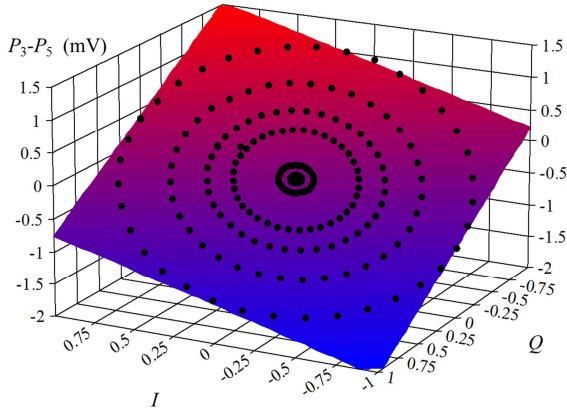
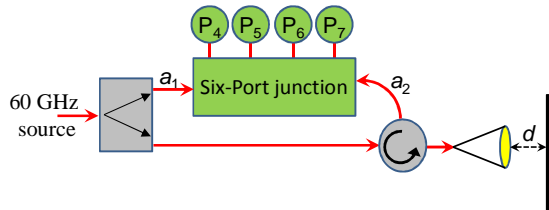


Fig. 4. IQ demodulation at 60 GHz: 3D complex interpolation – F=60 GHz. (● Measured data).

II. DISTANCE SENSING APPLICATIONS

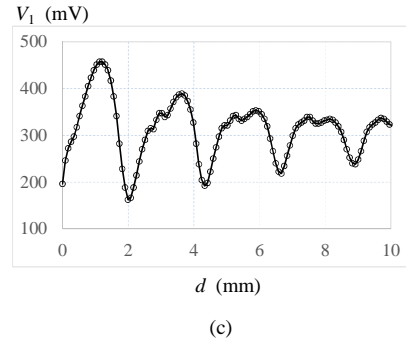
A distance measurement sensor based on the six-port demodulator associated to WR15 power divider, circulator and horn antenna is given in Fig. 5. The antenna with vertical polarization has been tested with stand-off d from contact to 10 mm to a metallic target. For example, detected voltage V_1 as a function of d shows the spread propagation losses that increase with d . Furthermore, resonances are related to wave recombination between the reflected wave by that target, the guided reflected wave at the antenna input (mismatch) and the free-space source match term (reflection of the received wave by the antenna). A dedicated free-space calibration method that takes into account these two effects can be implemented to derive the distance as a function of the measured voltages [10]. Complementary results will be shown in the last version of the paper.



(a)



(b)



(c)

Fig. 5. Free-space distance measurement – F = 60 GHz. (a) and (b) Experimental test bench. (c) Detected voltage V_1 as a function of the stand-off d .

V. CONCLUSION

A 60 GHz six-port IQ demodulator in WR15 guide technology has been designed and tested. On this basis, a free-space six-port reflectometer has been described for close distance measurement in the cm range. Preliminary experiments show propagation of spherical waves combined with free-space stationary waves. Future work will provide all necessary calibration procedure for accurate extraction of distance and precision analysis.

REFERENCES

- [1] G. Engen and C. Hoer, "Application of an arbitrary 6-port junction to power-measurement problems," *IEEE Trans. Instrum. Meas.*, vol. 21, no. 4, pp. 470–474, Nov. 1972.
- [2] J. Li, R. G. Bosisio, and K. Wu, "A collision avoidance radar using six-port phase/frequency discriminator," *Proc. IEEE MTT-S Dig.*, pp. 1553–1555, May 1994.
- [3] J. Osth, A. Serban, O. Owais, M. Karlsson, S. Gong, J. Haartsen, and P. Karlsson, "Six-port gigabit demodulator", *IEEE Trans. Microw. Theory Tech.*, vol. 59, no. 1, pp. 125–131, January 2011.
- [4] A. Koelpin, G. Vinci, B. Laemmle, D. Kissinger and R. Weigel, "The six-port in modern society," *IEEE Microw. Mag.*, vol. 11, no. 7, pp. 35–43, Dec. 2010.
- [5] A. Moscoso-Mártir, J.M. Ávila-Ruiz, E. Durán-Valdeiglesias, L. Moreno-Pozas, I. Molina-Fernández, A. Ortega-Moñux and J. de-Oliva-Rubio, "Butler matrix based six-port passive junction," *IEEE WiSNet*, pp.7–9, Jan. 2014.
- [6] S. O. Tatu, A. Serban, M. Helaoui and A. Koelpin, "Multiport technology: the new rise of an old concept," *IEEE Microw. Mag.*, vol. 15, no. 7, pp. 34–44, Nov. 2014.
- [7] B. Laemmle, G. Vinci, L. Maurer, R. Weigel, and A. Koelpin, "A 77-GHz SiGe integrated six-port receiver front-end for angle-of-arrival detection," *IEEE J. Solid-State Circuits*, vol. 47, no. 9, pp. 1966–1973, Sept. 2012.
- [8] A. Koelpin, F. Lurz, S. Linz, S. Mann, C. Will and S. Lindner, "Six-port based interferometry for precise radar and sensing applications", *Sensors*, vol. 16, no. 1556, pp. 1–26, Sept. 2016.
- [9] K. Haddadi and T. Lasri, "Formulation for complete and accurate calibration of six-port reflectometers", *IEEE Trans. Microw. Theory Tech.*, vol. 60, no. 3, pp. 574–581, March 2012.
- [10] K. Haddadi, MM.Wang, O. Benzaim, D. Glay, and T. Lasri, "Contactless microwave technique based on a spread-loss model for dielectric materials characterization", *IEEE Microw. Wireless Compon. Lett.*, vol. 19, no. 1, pp. 33–35, Jan. 2009.