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Nano-Positioning Test platform for Free-Space Six-Port Interferometric Distance Measurements

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Abstract— Continuous wave (CW) millimeter-wave radars have gained the interest from industry for accurate sub-wavelength distance measurements. In particular, the six-port radar architecture presents advantages such as high resolution combined with low-power consumption and low-cost implementation in the millimeter-wave regime. In this effort, a new test platform based on fully automated piezo-electric nano-positioning stages that simulates moving targets in XYZ directions with centimeter range combined with nanometer resolution is described. The test platform is crucial to yield performance metrics in terms of repeatability, sensitivity and accuracy. Preliminary experimental results considering a WR15 six-port CW radar designed and realized for harsh environment operation are presented to validate the approach proposed.

Keywords— six-port, millimeter-waves, free-space, radar.

I. INTRODUCTION

Precise positioning using millimeter-wave signals has attracted the interest from the research community [1]. In particular, six-port radar technology has been identified as an alternative to the conventional heterodyne architecture [2]. Generally speaking, the six-port is a passive structure based on the interferometric principle featuring two input ports and four output ports [3]. Six-port combines compactness, low energy consumption together with high measurement performance [4]. A variety of six-port systems have been exemplarily demonstrated in metallic guide, substrate integrated waveguide (SIW), planar and monolithic forms. Each technology presents own advantages and drawbacks [5]-[7]. The authors themselves have contributed to the dissemination of the six-port technology in various applications [8]-[19].

The penetration of six-port technology for industrial applications requires dedicated test set-ups to determine intrinsic performance and limitations. In this effort, we use a metallic waveguide six-port interferometer acting as an IQ demodulator operating at 60 GHz. The metallic waveguide technology provides isolation between nearby signals and presents immunity to environmental variations. In particular,

we introduce a new test platform for accurate distance measurements. This latter is built up with nano-positioning stages from SmarAct® and a high performance digital scope for six-port voltages acquisition. In section II, the experimental test platform and principle of operation are described. Experimental results are summarized in Section III.

II. EXPERIMENTAL TEST PLATFORM

The block diagram of the proposed distance measurement technique is presented in Fig. 1. The millimeter-wave set-up comprises a frequency synthesizer, waveguide six-port IQ demodulator, low noise amplifier, circulator and horn antenna. The system is completed by a piezo-based nano-positioning stage that holds a metallic target (dimensions = 3.2×4.2 cm²).

The six-port IQ demodulator is fed by the frequency synthesizer. The radar function is achieved using a single horn antenna working as transmitter and receiver. To that end, a circulator is included to deliver the received signal by the antenna to the second input port of the six-port IQ demodulator. A low noise amplifier is used to enhance the signal to noise ratio at the signal reception.

The test platform proposed has been fully automated under Labview® environment to set the measurement parameters (RF power, frequency, distance range and step) and to provide detected voltages under different measurement configurations. (Fig. 1). As a demonstration, experiments are considered for 60 GHz near field distance measurement from contact to stand-off set to 5 mm (2 free-space wavelengths). The target is moved along one linear stage in steps of 500 nm over the full range. The input signal is transmitted to the WR15 horn antenna that radiates the signal towards the target. The metal plate then reflects the signal back to the antenna receiving the signal and transmits it to the second input of the six-port radar.

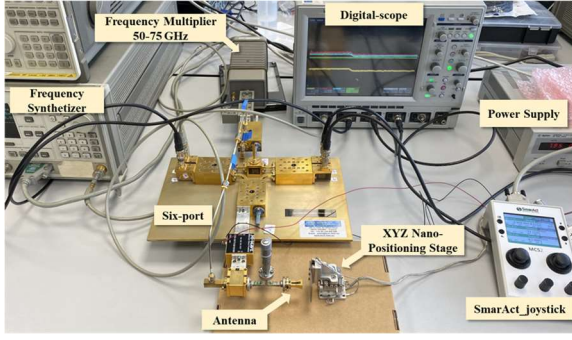


Fig. 1. Proposed test platform for mm-wave free-space distance measurement.

To achieve high measurement accuracy, the linearization (interpolation by a polynomial function) of the six-port detectors to eliminate the distortion of their electrical response is required (Fig. 2). To that end, the detected voltages are measured as a function of the input RF power to apply a linearization algorithm.

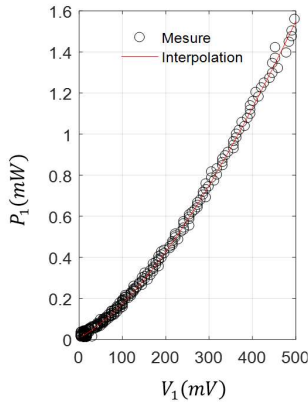


Fig. 2. Input RF power as a function of the measured voltage V_1 and polynomial interpolation.

From Fig. 2, we notice that the linearity is degraded by distortions. Consequently, 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 power P_1 is given by:

$$P_1 = -1.1265 \times 10^{-13} V_1^5 + 4.8194 \times 10^{-10} V_1^4 - 6.4135 \times 10^{-8} V_1^3 + 6.0750 \times 10^{-5} V_1^2 + 1.1082 \times 10^{-3} V_1 + 8.5 \times 10^{-2} \quad (1)$$

In a second step, guided measurements have been performed to yield intrinsic performance of the six-port IQ demodulator. To that end, a mechanically variable phase-shifter in WR15 technology has been used to control the phase-shift between the LO and RF signals. The theoretical detected output powers P_i ($i = 1, \dots, 4$) are given by

$$P_1 = b_3 \cdot b_3^* = \frac{1}{4} [A_1^2 + A_2^2 + 2A_1 \sin(\Delta\phi)] \quad (2)$$

$$P_2 = b_4 \cdot b_4^* = \frac{1}{4} [A_1^2 + A_2^2 - 2A_1 \sin(\Delta\phi)] \quad (3)$$

$$P_3 = b_5 \cdot b_5^* = \frac{1}{4} [A_1^2 + A_2^2 + 2A_1 A_2 \cos(\Delta\phi)] \quad (4)$$

$$P_4 = b_6 \cdot b_6^* = \frac{1}{4} [A_1^2 + A_2^2 - 2A_1 A_2 \cos(\Delta\phi)] \quad (5)$$

where $\Delta\phi = \phi_1 - \phi_2$ is the phase shift between the two input LO and RF signals.

The operating frequency is set to 60 GHz and the relative phase-shift ($\Delta\phi$) is varied from 0 to 360° with step of 10°. The I and Q components related to the ratio between the LO and RF signals are given by

$$I = 10^{\frac{A}{20}} \cos(\Delta\phi) \quad (6)$$

$$Q = 10^{\frac{A}{20}} \sin(\Delta\phi) \quad (7)$$

Fig. 3 shows the detected voltages V_1 and V_3 as a function of $\Delta\phi$. The detected voltages present a sinusoidal shape and are in quadrature, in accordance with (2) to (5).

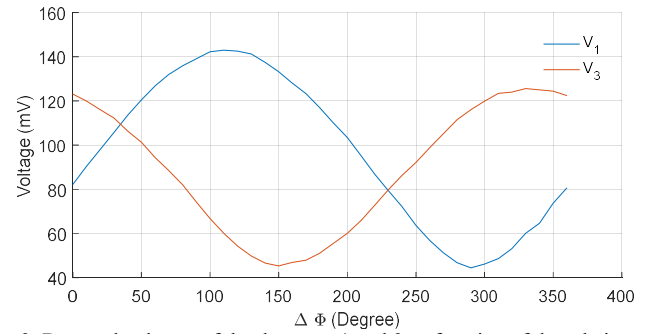


Fig. 3. Detected voltages of the detectors 1 and 3 as function of the relative phase-shift $\Delta\phi$ between the RF and LO signals- $f=60$ GHz.

Finally, free-space application is considering by moving the target from a distance separation d between the antenna aperture and the planar metallic target between 0 (contact) to 5 mm (two free-space wavelengths at $f=60$ GHz). The four detected voltages as a function of the distance d are given in Fig. 4. Qualitatively, a good measurement sensitivity to the distance is noticed. The shapes of the curves are not sinusoidal as the target is located in the vicinity of the antenna, in the near-field. In addition, free-space multiple reflections between the antenna aperture and the target yield to signal distortion. Consequently, analytical modeling of the free-space propagation is needed to accurately extract the distance to the target. Fig. 4(c) presents V_3-V_4 as a function of V_1-V_2 that should exhibit graphically a circle centered on 0 for an ideal configuration. An elliptical behavior related to the system imperfections is noticed.

These results are instructive as they demonstrate a good measurement sensitivity with high signal to noise ratio. The proposed experimental set-up does not induce non-systematic errors and other sources of perturbation brought by the operator when the target is moved manually. An analytical model associated to a free-space calibration procedure will be considered in future works to extract the distance from the detected voltages.

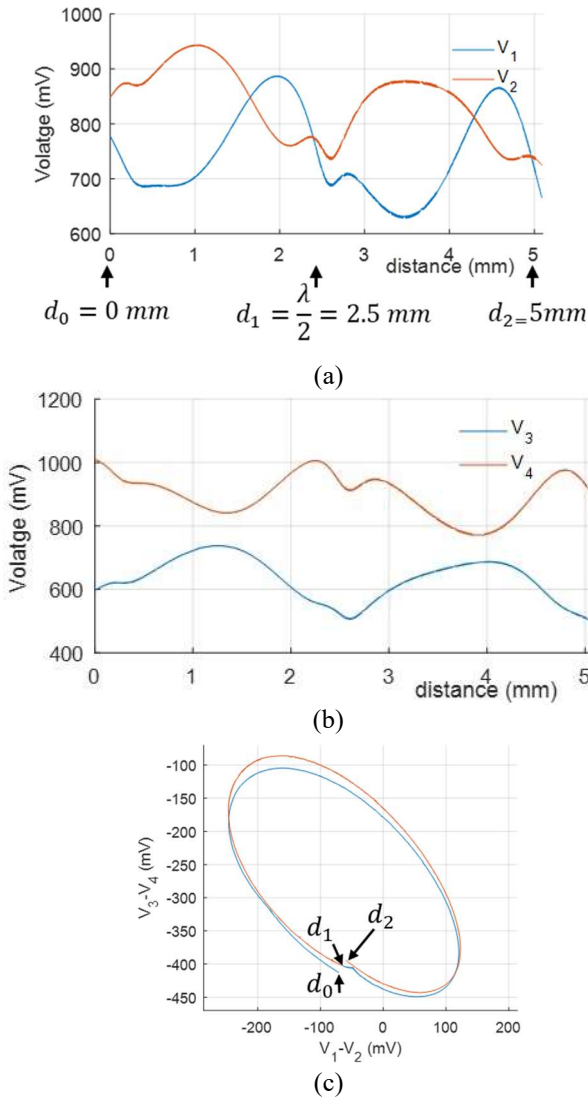


Fig. 4. Detected voltages of the detectors 1 and 3 as function of the distance separation between the antenna aperture and a metallic target - $f=60$ GHz.

III. CONCLUSION

A fully automated test platform dedicated to short distance measurements has been proposed. This latter is based on piezo-electric nano-positioning stages that simulates moving targets within centimeter range and nanometer resolution. Preliminary experiments considering a monostatic six-port radar realized in metallic WR15 technology are promising. Future works will include full modelling for the resolution of the inverse problem, i.e. determination of the distance from the detected voltages.

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