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Repeatability of Programmable Waveguide Attenuators at 110-170 GHz and 220-330 GHz

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***Abstract*—Variable waveguide attenuators are electromechanical components that are used to vary signal levels during RF measurements. Mechanical turn knobs or millimeter screws with a human setting have been used to vary the RF signal level from the attenuator. In particular, waveguide attenuators are needed with modulated signal measurements above 100 GHz frequencies due to the limited output power control ranges of signal generators. One of the requirements of automated measurement systems is that all system components can be programmable with computers.**

This paper proposes a software programmable approach that controls a mechanical knob turning of the waveguide attenuator. A stepper motor with a step angle of 1.8 degrees was attached to two standard waveguide attenuators. The repeatability analysis of the measurement results showed that the standard deviation of the attenuation variation of the setting can be reduced to 0.05 dB at 110 to 170 GHz and 0.1 dB at 220 to 330 GHz. The proposed method of attaching a stepper motor to the waveguide attenuator enables accurate measurements of the modulated conductive and radiative 6G signal with a wide dynamic range.

Index Terms – 6G, D-band, programmable control, repeatability, sub-terahertz, variable attenuator, waveguide

I. INTRODUCTION

The sixth generation (6G) mobile networks are expected to provide significantly higher data rates and lower latency compared existing 4G or 5G networks [1]. The 6G extreme data rate systems aim to occupy sub-terahertz (THz) frequencies from 100 GHz up to 300 GHz. These frequencies are studied for 6G wireless communication systems, which are expected to be launched in 2030, following the United Nations Sustainable Development Goals targets [2]. The first standard that utilizes these sub-THz frequencies for telecommunication purposes is Wireless Fidelity (Wi-Fi) standard IEEE 802.15.3d, which offers a 100 Gbps data speed link and cell coverage distances ranging from tens of centimeters to a few hundred meters [3]. The utilization of sub-THz frequencies has several challenges compared to their lower frequency counterparts, e.g., shorter link distance requiring denser base station installations or the use of large antenna arrays to improve signal coverage area [4].

Waveguide attenuators are crucial components of 6G measurements which are performed above 110 GHz frequencies which is the highest frequency which coaxial 1.0 mm connector supports. They are used to control RF signal levels and enable linear operation or protect the damage signal level of the reception frequency extender. The waveguide attenuators can be either fixed or variable in terms of provided attenuation level. A waveguide-based THz variable attenuator that is incorporated with a piezoelectric motor for finer tuning, operating from 500 to 750 GHz with up to 40 dB attenuation is presented in [5]. Most variable waveguide attenuators are implemented in rectangular air clearance with a dielectric slab. This clearance can be varied by an external actuator to control the general attenuation [6]. It is possible to use a pin diode bias as an attenuator tuner as presented in [7], working in Ka-band and ranging between 1.2 to 15 dB of attenuation value. There is also a photonic approach to apply a controllable attenuation range in attenuators operating at 300 GHz [8].

The variable standard waveguide attenuators used in this work operate at 110-170 GHz and 220-330 GHz and those are manufactured by Elmika [9]. These variable waveguide attenuators are typically adjusted by knobs that change the length of a waveguide section or a resistive load to vary the signal attenuation. However, the manual setting of this kind of attenuator is prone to human errors, leading to some inconsistencies in attenuation, as expressed in this previous work [10], measured by repeatability analysis. Repeatability is the measure of a component or system producing the same result in multiple rounds when the same settings are applied under identical conditions. On the other hand, the accuracy is a measure of how close a measurement is to the true or mean value [11]. The high repeatability ensures that measurements are consistent between others, while the high accuracy minimizes the potential for errors in each measurement time.

In this paper, a programmable adjustment on the system of manually operated variable waveguide attenuators with a stepper motor is proposed. The performance of the proposed system is evaluated by measuring the repeatability and the accuracy of attenuation values.

II. THE VARIABLE WAVEGUIDE ATTENUATOR MEASUREMENT SETUP

A fully automated S-parameters measurement setup to characterize variable waveguide attenuators by S-parameter measurements is presented in Fig. 1. The system consists of a Keysight Network Analyzer PNA-X N5242B (900 Hz-26.5 GHz), transmission (Tx) and reception (Rx) frequency extenders manufactured by Virginia diodes) which support 110-170 GHz and 220-330 GHz frequency bands, off-the-shelf mechanical variable attenuators operating at 110-170GHz and 220-330GHz manufactured by Elmika, a stepper motor (model: 17HS4401, step of 1.8 degrees), microcontroller with H-bridge circuit (ATmega328P), motor power supply, and a

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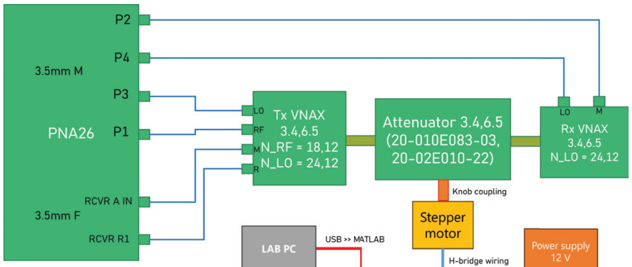

Fig. 1: A full automated S-parameters measurement setup with a variable attenuator as a device-under-test (DUT).

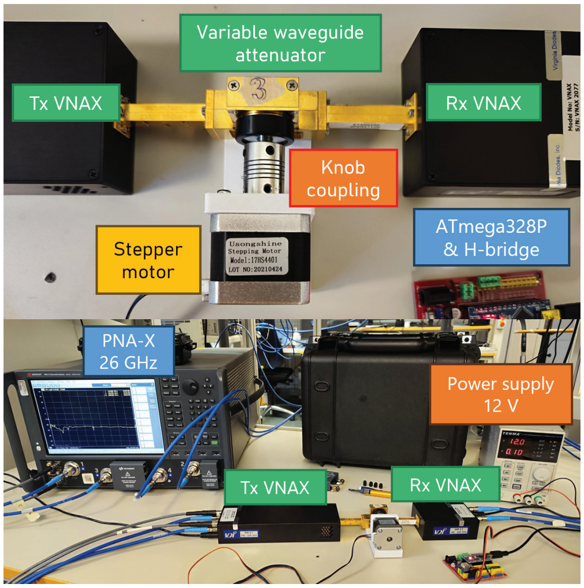

Fig. 2: Photos of a real experimental setup in the laboratory, (top) top-view and (bottom) side-view.

controlling computer. The photograph of the measurement system is shown in Fig. 2.

Frequency extenders were calibrated first with a waveguide calibration kit. The reference plane was set in between the transmitter and receiver extenders.

Vector network analyzer frequency extenders (VNAX) at both ends of Tx and Rx, from Virginia Diodes Inc. (VDI), were used to convert signals up and down, respectively, between an intermediate frequency (IF) and a radio frequency (RF). These frequency extenders multiply the measurement IF signal up to the RF frequency. In this paper, two VNAX models are used, WR6.5 operates at 110-170 GHz, and WR3.4 supports the 220-330 GHz. The VNAX frequency extenders are intended to operate only with sinusoidal continuous wave (CW) signals.

The frequency extenders used do not have a built-in gain controller, and those operate with a fixed output power level with the nominal input signals. The variable waveguide attenuator is needed to vary the output power, and attenuator models VA-02 (WR6.5) and VA-012 (WR3.4) were used during the studies. Both models provide an attenuation range about 40 dB. These attenuators can adjust the attenuation from minimum to maximum with a single rotation of the disk having 35 numbers on a knob-setting disk.

The S-parameter measurements focused on the S_{21} or attenuation measurements of the variable attenuators over a corresponding frequency band (110-170 or 220-330 GHz). The IF resolution bandwidth was set at 1 kHz at the IF frequency of 279 MHz. All results went through an averaging factor of 1, with 5 sweeps per knob value, 4 iterations, and 2 directions of knob rotations of clockwise (CW) or counter-clockwise (CCW). From these parameters, 40 repeated measurements were obtained for each 6401 frequency point.

III. THE AUTOMATED CONTROLLING PLATFORM

According to the setup shown in Fig. 1, the stepper motor was attached to the mechanical turning knob of the attenuator with a flexible coupler. The motor has a step resolution of 1.8 degrees and 5 percent angular accuracy or drift. A supply voltage of 12 V was fed into the motor through an H-bridge circuit providing motor movement. The H-bridge circuit was controlled by an ATmega328P-based microcontroller board connected to a host computer via a USB interface. Using a MATLAB script, the microcontroller board is utilized to transmit position commands to the motor sent from the computer.

A. *Motor Control and Data Acquisition Sequences*

The MATLAB's serial communication commands were relayed to the microcontroller and then sent as an electrical signal, which determines the distance and direction of rotation to the motor. First, a command to configure a serial bus is initialized on the COM5 port with a fixed baud rate of 9600. After that, a motor command can be sent to the stepper motor. It is sent as a serial print function to specify the rotation distance and direction. The number '40', which is the smallest micro step, represents one division out of 35 divisions of all attenuator's knobs in the clockwise direction. Therefore, the exact position of knob settings can be achieved by a multiple of micro steps calculation accompanied by a numerical sign of plus or minus for directions. After this phase, a script to control the PNA-X is compiled, beginning with frequency range, points, input power, and the number of sweeps definition. A measurement sequence then acquires S-parameters as a data block in matrix form that can be post-processed directly within the MATLAB environment.

B. *Repeatability and Accuracy Calculation*

When all required S-parameter data is ready, it is first plotted for a whole frequency band to observe a 'hysteresis' that implies the repeatability of each variable attenuator. Hysteresis is a measure that determines the dependence of a specific component or a system on its historical state. In this paper, there is a difference in the S21 value between one direction of changes in the settings of the attenuator knob compared to another direction. Without hysteresis, each exact position of the knob must produce the same attenuation level, whether it is adjusted clockwise or counter-clockwise. The

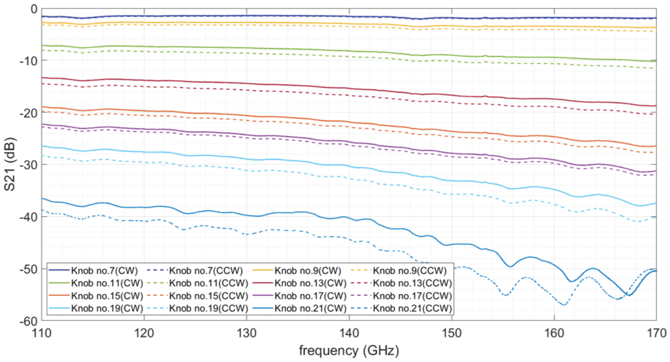

Fig. 3: Attenuation response of the variable waveguide attenuator, operating at 110-170 GHz with knob settings variation.

measurement accuracy is determined based on the calculated standard deviation of S21 among all 40 repetitions in each of the knob values.

IV. Repeatability and Accuracy Analysis of Waveguide Attenuators at 110-170 GHz and 220-330 GHz

The absolute attenuation levels of the variable attenuator operating in the 110-170 GHz frequency range with different attenuation settings are shown in Fig. 3. The mean values presented are based on 20 iterations of each movement direction in Fig. 3. The range of knob values varied from 7 to 21, where the attenuator has a significant signal attenuation range. The attenuation is constant over the whole frequency band in the knob range of 7 to 11, corresponding to 2 dB to 10 dB attenuations, respectively. The attenuation level tends to linearly increase after the knob value of 13, and it continues to attenuate more exponentially up to knob 21 with a strong fluctuation around the end of the band, corresponding to about 40 dB to 50 dB of attenuation. Moreover, the hysteresis phenomenon is visible from the result deviation between clockwise and counter-clockwise knob movement. The value difference is at the lowest of 0.5 dB and the highest value of 4 dB, increasing with more absolute attenuation.

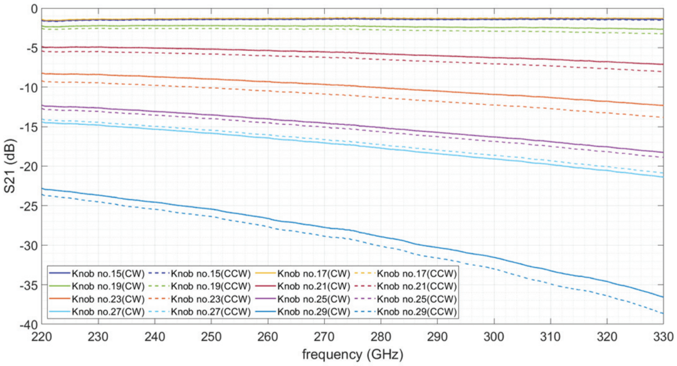

Fig. 4: Attenuation response of the variable waveguide attenuator, operating at 220-330 GHz with knob settings variation.

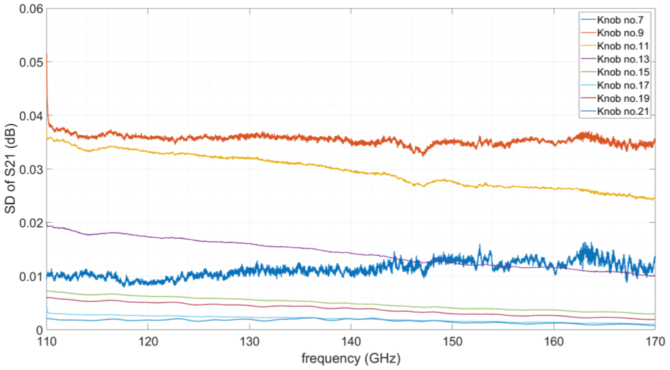

Fig. 5: A standard deviation of attenuation on the waveguide attenuator, operating at 110-170 GHz with different knob settings and over 40 iterations.

The figure presented in Fig. 4 shows the absolute attenuations of the 220-330 GHz attenuator. The study is carried out for knob settings of 15 to 29, which correspond to attenuation levels ranging from 1.2 to 40 dB. The figures Figs. 3 and 4 reveal similar trends of increasing linear attenuation roll-offs over the frequency bands. However, there is less ripple at the highest attenuation levels in the 220-330 GHz attenuator than its lower frequency counterpart. Additionally, there is a hysteresis between clockwise and counter-clockwise knob rotations from 0.25 dB up to 2 dB apart, which is much lower compared to this behavior in the WR6.5 attenuator. These results indicate that each waveguide attenuator must be evaluated individually, and the frequency dependency of those needs to be recorded and analyzed carefully to enable accurate RF measurements.

A standard deviation (SD) of 110-170 GHz attenuator measurements results with selected knob settings are presented in Fig. 5. The SD of 0.001 dB at the lowest attenuation value and 0.05 dB at the highest attenuation are observed in the variation range of 0.1 dB to 9 dB, calculated from max-min attenuation at each frequency and knob. The results of the attenuation variation of S21 analysis for the 220-330 GHz

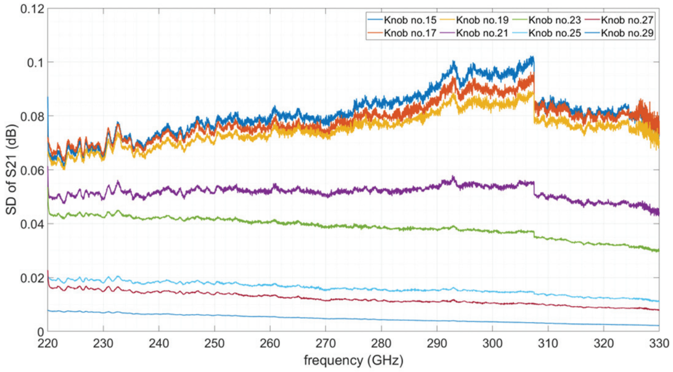

Fig. 6: A standard deviation of attenuation on the waveguide attenuator, operating at 220-330 GHz with different knob settings and over 40 iterations.

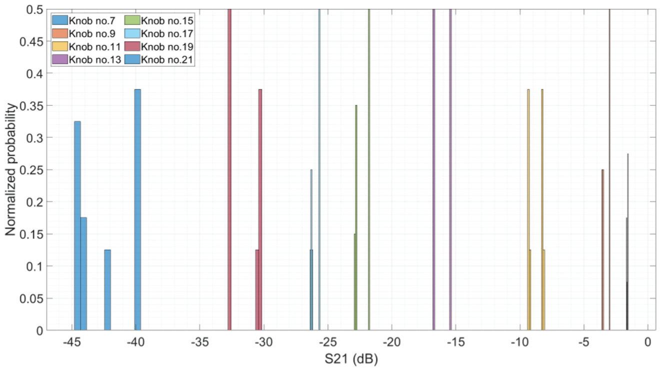

Fig. 7: S21 histogram of 110-170 GHz waveguide attenuator (WR6.5) with a knob range of 7-21 , at 140 GHz center frequency.

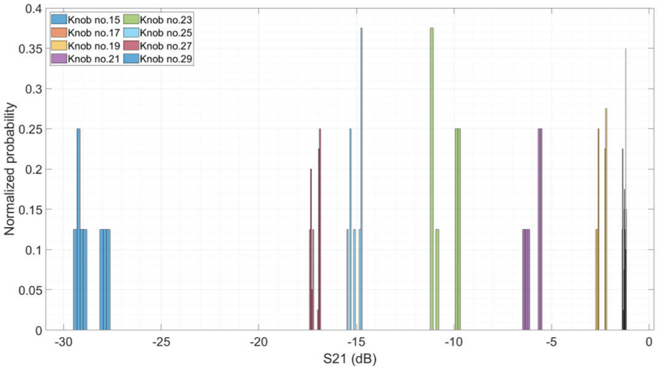

Fig. 8: S21 histogram of 220-330 GHz waveguide attenuator (WR3.4) with a knob range of 15-29, at 275 GHz center frequency.

attenuator is shown in Fig. 6. The standard deviation for 220-330 GHz is considerably higher than the 110-170 GHz and at the same attenuation the variation is two times higher while in the smaller variation range of 0.05 to 3 dB.

The proposed stepper motor-controlled waveguide attenuator significantly improves the accuracy of the power control compared to the human operating attenuator. The same 220-330 GHz waveguide attenuator was used in previous work [10]. The proposed stepper motor approach reduced SD from 0.35 dB down to 0.1 dB. However, the studied attenuator has a discontinuity in the repeatability at 307 GHz, but it can be mitigated as the system went through higher attenuation levels. The fundamental reason for the measured discontinuity in the attenuation repeatability curves was not found.

Attenuation setting distributions of the variable attenuators WR6.5 and WR3.4 are presented in Fig. 7 and Fig. 8, respectively. The spread of S_{21} values at 275 GHz is much narrower and constantly aligned with the same attenuations in comparison to the data at 140 GHz. This means that the attenuation adjustment in 220-330 GHz attenuator is more linear and accurate. The hysteresis, which means a difference in data at the same position with different direction of attenuation knob, can also be observed in these distribution plots. In a single-knob setting, there is a visible gap separating one distribution group from another. Therefore, this behavior confirms a repeatability error as it was seen in the previous figures of the absolute attenuation levels.

V. CONCLUSION

This paper studied the repeatability and accuracy of two variable waveguide attenuators in frequency ranges of 110-170 GHz and 220-330 GHz. The measured total variation range is 0.2 dB ($\pm 2\sigma$) for the 110-170 GHz attenuator and 0.4 dB ($\pm 2\sigma$) for the 220-330 GHz attenuator. These results indicate a considerably small repeatability error for the mean values that enables an accurate RF measurement system. The repeatability hysteresis error between automated clockwise and counter-clockwise knob turning is about 0.25 dB to 4 dB depending on the operating frequency ranges and knob setting. The measurement system implemented in this work was carried out mainly using motorized modules consisting of a stepper motor, a flexible coupler, and a microcontroller. The MATLAB script can be used to convey a command indicating positions and turning directions of the attenuators, which was executed in sequences with the data acquisition. The typical SD variation of attenuation in this proposed approach was reduced to 0.1 dB compared to 0.35 dB of the manual approach presented in [10].

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