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PAPERS

Waveguide power phase shifter with a ferrite circulator in S-band

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This paper presents the application of a phase shifter with a ferrite Y-circulator in band S. Global literature addresses primarily the basic types of power waveguide phase shifters, however, there has been minimal literature on a phase shifter that uses a ferrite circulator for phase shifting. The paper describes theoretical and practical results where a ferrite circulator is used to shift the phase. A power phase shifter utilizing a ferrite circulator could be used in power applications where high demands are placed on the phase shift accuracy with minimal power losses. The phase shift is handled by a tunable waveguide short circuit that is connected to the port 2 of the ferrite circulator. By changing the waveguide length, the phase is changed. The measured results are compared with theoretical calculations and evaluated. The proposed phase shifter utilizing the ferrite circulator has its advantages in its simple design, in the accuracy of the phase adjustment and in the speed of the tuning. Another great advantage is its quite low cost due to its simple design.

K e y w o r d s: ferrite circulator, s-parameters, rectangular waveguide, dielectric, port, phase

1 Introduction

The open literature related to power phase shifters describes five basic types of power phase shifters used in a rectangular waveguide path:

- a rectangular phase shifter with cross-sectional change,
- a phase shifter with a laterally sliding dielectric plate,
- a knife phase shifter,
- a phase shifter with a lengthwise sliding dielectric plate,
- a rotary phase shifter.

In these basic types of power phase shifters, the phase angle $\Psi = \beta l$ of the traveling wave propagating through the waveguide can be altered. Their design uses one of four basic principles:

- changing the length l of the waveguide,
- changing the measured displacement β of the waveguide by changing the cross-section,
- changing the measured displacement β of the waveguide by the movement of the dielectric parts within the waveguide,
- changing the planar polarization of the basic vid of a circular waveguide into a circular polarization, in which a phase shift is achieved by the rotating dielectric part and the reverse transformation of the circular polarization into a planar one [1].

These basic configurations use the basic power phase shifters introduced above, which are continuously modified and improved [2-6]. Literature [2-6] mainly deals with phase variation by changing the dimension of the rectangular waveguide. The actual change of the rectangular waveguide dimension is done by inserting various dielectric and ferrite plates into the waveguide. The production of such phase shifters is extremely complex and expensive as it is necessary to achieve high precision of the elements that are inserted into the rectangular waveguide.

Each introduced power shifter has its own advantages and disadvantages that are directly related to their own design. For this reason, it was necessary to find a phase shifter design that could have the advantages of the previously mentioned power phase shifters while having as few drawbacks as possible. For power phase shifters, the primary focus is on the accuracy of phase shifting, speed of phase adjustment and minimum power losses. One such possible solution is to use a power ferrite Y-circulator to change the phase.

A possible solution of using a ferrite circulator to change the phase is outlined in the literature [7,8], however, the solution presented in this paper is different. This paper proposes another possible method for phase shifting, where a power ferrite Y-circulator is used for phase shifting. It is a potential solution that could be used at high or very high-power levels. The presented article deals with outputs in the order of kW (kW - level). The use of the presented concept of a power phase shifter with the use of a ferrite circulator can be used in equipment for interference of electronic systems, for example for the needs of determining the resistance to EMC.

2 Waveguide power phase shifter with ferrite circulator

The concept of the proposed phase shifter is depicted Fig. 1 (the three-armed ferrite circulator consists of a starry triangular gate and is described in detail in [1]). The tunable waveguide shunt (piston) is connected to the

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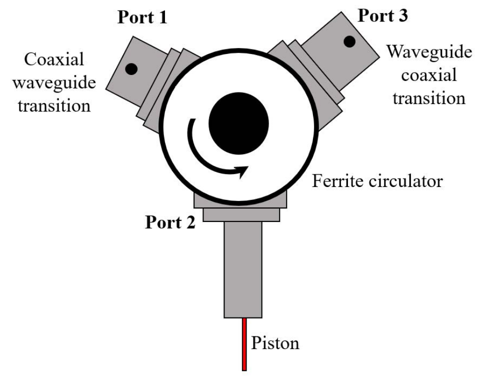

Fig. 1. Concept of the proposed phase shifter

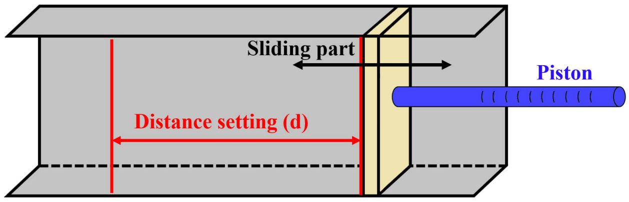

Fig. 2. Tunable waveguide shunt (piston)

ferrite circulator at port number 2. By gradually retracting the piston (Fig. 2), the length of the waveguide path is changed, and a phase shift occurs. No dielectric and metal pins are involved in the described phase shifter; hence it is suitable for HPM power applications.

The power ferrite Y-circulator used is designed for Full Microwave Power 1.2 kW. When tested for Microwave Power 1.0 kW, its parameters were Isolation 25.9 dB, Insertion Loss 0.18 dB and Input Return Loss 22.5 dB. The presented ferrite circulator can transfer a maximum power of 1.21 MW in pulse mode. This value is due to the design of the used ferrite circulator. The average power shall not exceed 1.2 kW. If the ferrite circulator is to be operated in pulsed mode, the duty cycle must be considered to maintain the maximum average power.

For our application, a waveguide type R32 is used (for dry air it must not exceed the penetration magnitude of the electric field intensity $E_{\max} = 30\,\text{kV/cm}$, where the maximum power in pulse mode transmitted by the dominant mode TE_{10} in the waveguide is 7.81 MW. [1].

3 Phase shifter with ferrite Y-circulator without load

The functionality of the circuit of the power phase shifter with the ferrite circulator was first verified by practical verification without power load.

3.1 Practical verification of the functionality of the circuit without power load

For testing the functionality of our phase shifter design, a measurement station was set up. Figure 3 shows the phase shifter using a ferrite Y-circulator. The signal is delivered to port 1 of the ferrite circulator using a coaxial-waveguide transition. A tunable waveguide shunt is connected from the other side of the ferrite circulator. The parameters of the waveguide shunt are changed by a piston that is manually inserted into the waveguide. Manual adjustment of the piston position is accomplished by a rotary gear that moves the piston inside the waveguide. The distance of the piston can be read on a measuring scale. The actual insertion of the piston into the waveguide is managed by a rotary screw. The phase shifted signal is measured at the waveguide-coaxial transition, which is connected to port number 3 (output) of the ferrite circulator.

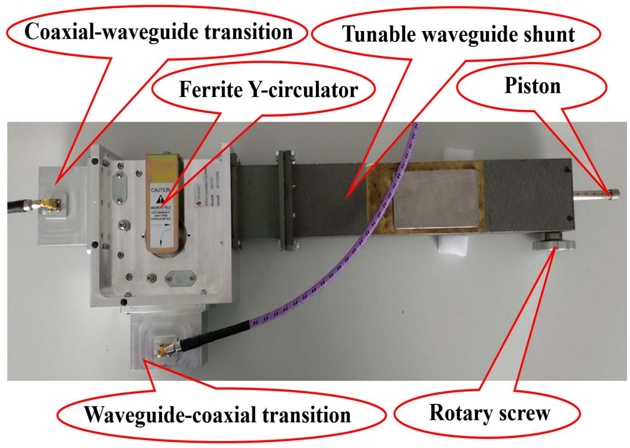

Fig. 3. The measuring station

3.2 Measurement results without power load

All measurements were performed at a frequency of 2.45 GHz. The measurements were made for the ten piston positions and the measured phase of the s_{21} parameter is summarized in Tab. 1 and Fig. 4.

Table 1. Phase dependence on piston distance

Position	Piston position d (cm)	Measured phase s_{21} (deg)
1	26.8	94.72
2	25.8	55.46
3	24.8	20.99
4	23.8	-13.45
5	22.8	-32.44
6	21.8	-68.72
7	20.8	-93.56
8	19.8	-118.02
9	18.8	-143.83
10	17.8	-171.53

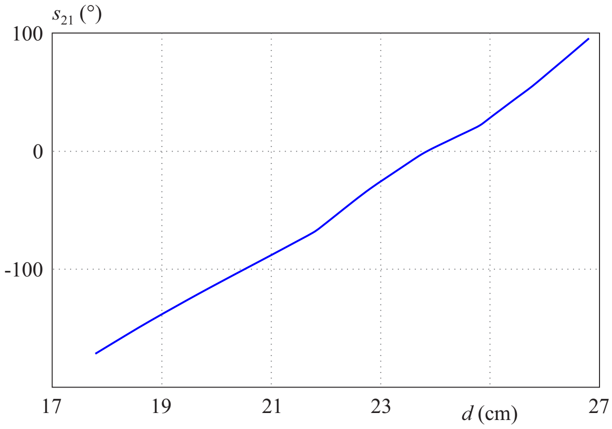

Fig. 4. Phase change of the s_{21} parameter depending on piston distance

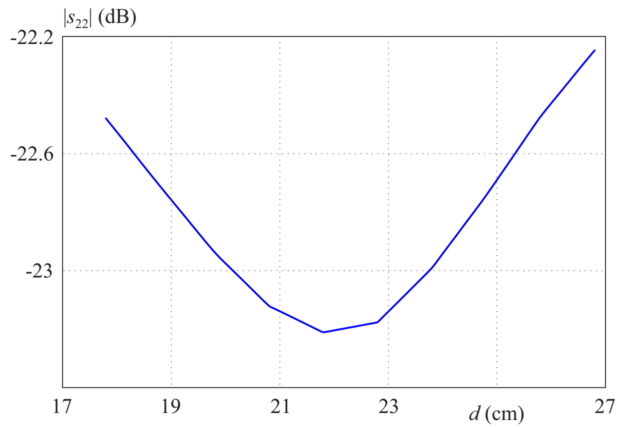

Fig. 5. Dependence of $|s_{22}|$ on distance

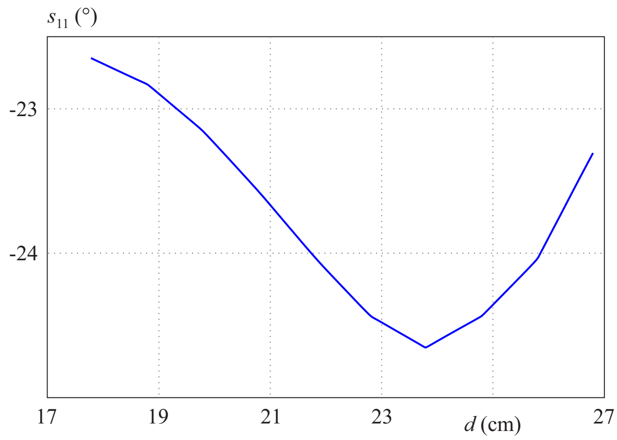

Fig. 6. Dependence of phase s_{11} on distance

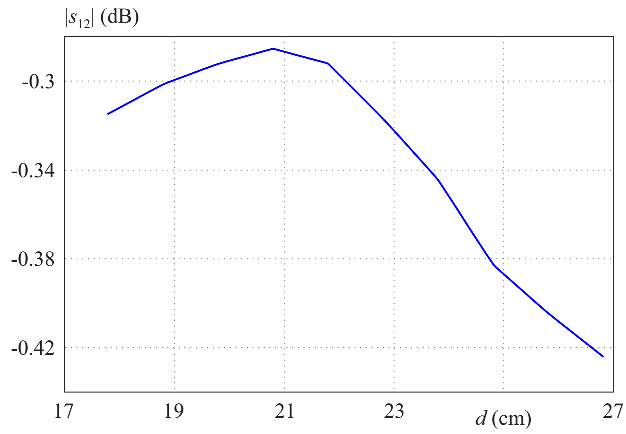

Fig. 7. Dependence of $|s_{12}|$ on distance

Before the actual measurement, the distance of the piston in the waveguide short circuit was measured in order to have an initial value (zero phase shift). During the measurement, it was found that the zero phase shift was at a value of 17.8 cm from the nozzle of the port 2 ferrite circulator. The entire measurement was performed for ten piston distances from the nozzle of the port 2 ferrite circulator.

Figures 5, 6 and 7 show the additional measurement results necessary for the confirmation of the theory that a ferrite circulator can be used as a phase shifter. It can be seen from the figures that the parameters $|s_{22}|, |s_{12}|$ and the phase at the input (port 1 of the ferrite circulator) vary slightly. These changes have minimal effect on the function of the phase shifter.

3.3 Simulation

To to verify the functionality of the circuit, analysis and simulation of S-parameters [9,10] were performed. For the comparison of practical and simulated results, the simulation of the s_{12} parameter is important. Parameter s_{12} is the backward transfer coefficient at the input terminated by the matched load. This is addressed in the literature [11 -17].

Simulation was performed for each piston distance (the position 1 to 10) at the operating frequency of 2.45 GHz. The resulting dependence of the phase parameter s_{21} is linear. Figure 8 shows the comparison of the theoretical results with the measured results of the phase change.

It can be seen from Fig. 8 that the line representing the phase shift is slightly waved. This waviness was caused by a measurement error. For this reason, a straight-line approximation is still needed (Fig. 9).

The resulting approximated line is $\varphi = 29.08d - 694.4$. The coefficient of determination or quality measure of the regression model is close to 1 (0.9963). The results show that the measurement fits our application.

4 Verification of the phase shifter under power load

4.1 Description of the measuring station

A special test station was set up for practical verification of functionality (Fig. 10). A specially designed power generator [18,19] was used as a source of a high-frequency electromagnetic field with high power. The transmitted high power signal is delivered to port number 1 of the ferrite circulator. Using a tunable waveguide shunt, which

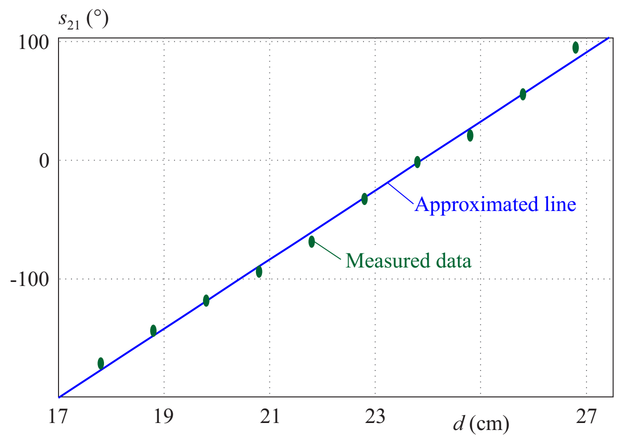

Fig. 8. Results of the approximation with real measured data

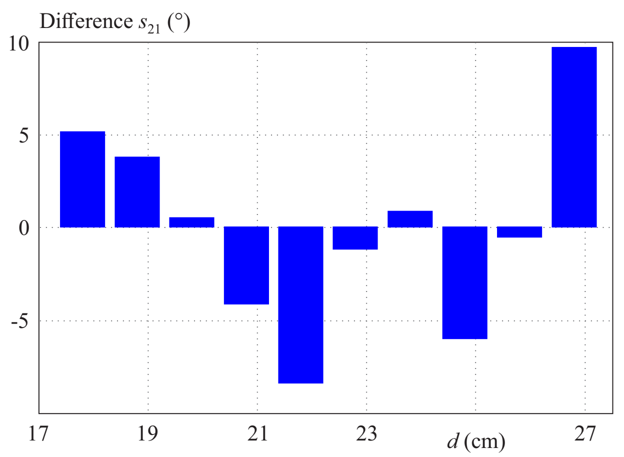

Fig. 9. Results of the approximation with real measured data

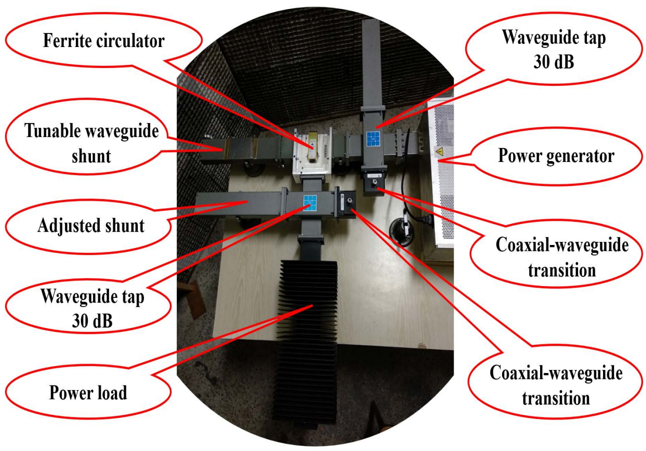

Fig. 10. Design of the measuring station

is marked, the phase shift is set. The tunable waveguide shunt is connected to port number 2 of the ferrite circulator. A matched power load is connected to port number 3 of the ferrite circulator. The circuit includes waveguide taps with an attenuation of 30 dB. The waveguide taps are needed in order to prevent destruction of sensitive measuring instruments. In addition, a 20 dB coaxial attenuator has been added to the input and output to protect the sensitive measuring instruments. A power load is connected to port 3 of the ferrite circulator.

4.2 Phase shift measurement

The measurement of the phase shift change was performed using a tunable waveguide shunt (Fig. 1). The change in waveguide length or the phase change is controlled by the movement of the piston. Measurements were performed for 10 measurement values. The piston was inserted into the waveguide at 1 cm increments. One centimeter of piston displacement in the waveguide represents a phase shift of 36°. The measurement results are shown in Fig. 11, where the dashed wave is the input signal (measured at port 1 of the ferrite circulator) and the other waves are at the output (measured at port 3 of the ferrite circulator). The figure shows ten successive measurements with a phase shift from 0 to 360°. It can also be seen from the measured values that the amplitude of the input signal (dashed signal) shows minimal change from the measured output signals. This means that there is negligible power loss on the ferrite circulator. The power losses are further described in 4.3.

From the overall measured data, the high-power phase shifter using the ferrite circulator is operating correctly.

Figure 11 shows the phase shifts, which are represented by a sinusoidal waveform. The measurement results show that each piston position displaced by one centimeter corresponds to a phase shift of 36°. This means that the phase shifter using the ferrite circulator is working correctly. Further measurements were made with subtle adjustments of 0.5°. A phase shifter using a ferrite circulator was able to set even such a small phase shift.

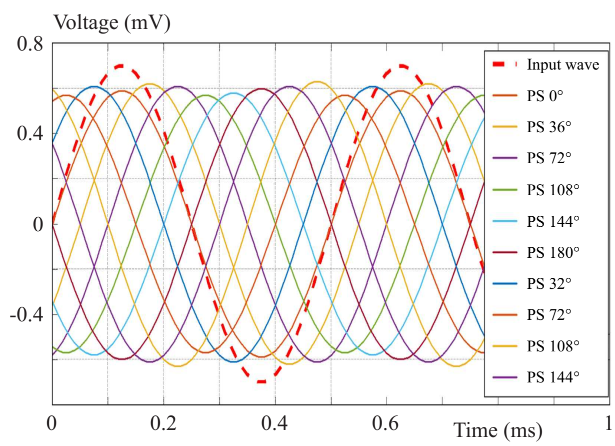

Fig. 11. Representation of phase shift for piston positions 1-10

4.3 Power losses on the ferrite circulator

The power loss measurements were performed using a Boonton RTP5340 power meter [20]. This device was connected through a waveguide tap with 30 dB damping and a coaxial attenuation cell of 20 dB. The measurements showed that the input mean power value was

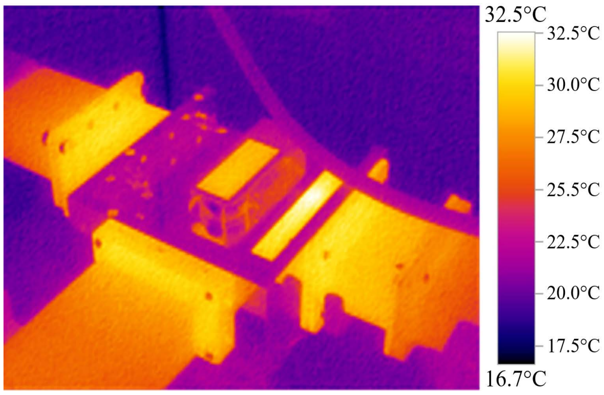

Fig. 12. Ferrite cilculator heating after 30 minutes at full load

3.401 dBm. After accounting for damping, the resulting mean power value was 24.01 dBW (approximately 218.82 W). The peak input power was 9.944 dBm, where after accounting for 50 dB damping the actual measured value was 29.944 dBW = 987.19 W.

The measured value of the output mean power was 3.304 dBm. After accounting for 50 dB damping, the actual value was 23.3 dBW (approximately 213.9 W). The measured peak power of 9.8 dBm after accounting for 50 dB damping had an actual value of 29.8 dBW (approximately 951.6 W).

The measurement results show that there is a negligible power loss of 4.85 W on the ferrite circulator.

4.4 Temperature dependence

The waveguide route (the eferrite circulator and tunable waveguide shunt) was also tested for temperature dependence. The temperature dependence is a very important parameter of the phase shifter in terms of its proper functionality. The measurements were made using a thermal imager to see how the ferrite circulator and the entire measuring station heats up at full power load. Figure 12 and Fig. 13 show how the measuring station warmed up after 30 minutes at full load. Using temperature dependence measurements, it was confirmed that there is minimal power loss on the ferrite circulator and piston.

The ferrite circulator warmed up to approximately 31° at the ports after 30 minutes of full load. The piston temperature remained almost unchanged. For interest, Fig. 14 shows the temperature at the matched power load, which was close to 120°.

The applied power load is dimensioned to a maximum average power of 1 kW.

5 Conclusion

This paper describes the possible use of a power ferrite Y-circulator for a power phase shifter. The main objective was to verify the functionality of the proposed circuit. From the practical measurements and theoretical results, it can be seen that the proposed power phase shifter using a ferrite Y-circulator is functional. The phase shifter using a ferrite circulator is a simple application with the capability of very accurate phase change with minimum conduction losses (power loss 4.85 W at a pulse

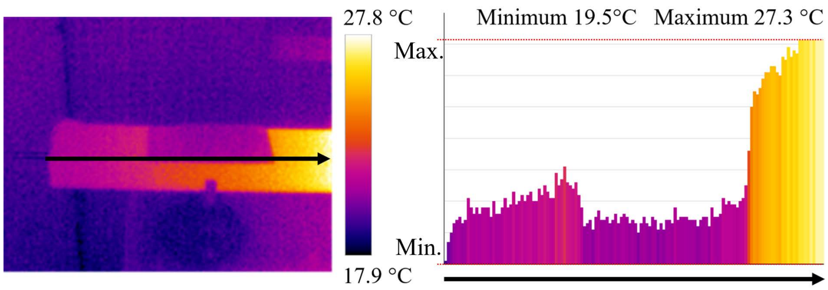

Fig. 13. Piston heating after 30 minutes at full load

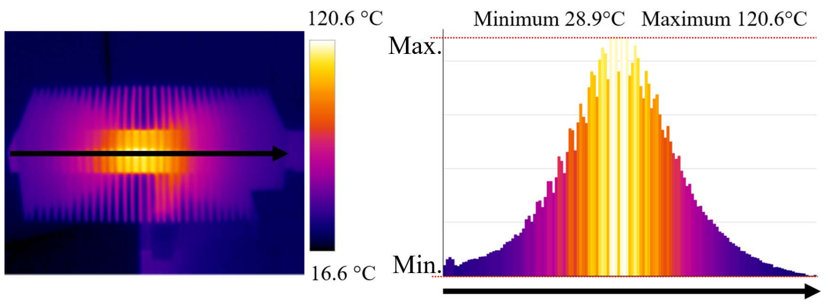

Fig. 14. Heating of the matched power load after 30 minutes at full load

power of approximately 1 kW). From the simulated results and measured values, it can be seen that the proposed power phase shifter using a ferrite Y-circulator is suitable for high-power applications. The small scatter of the measured values will not significantly affect the resulting phase shifting, as such scatter is negligible for high-power applications (the coefficient of determination or quality measure of the regression model is close to 1 (0.9963). The minor ripple (Fig. 4) was caused by manual control of the piston. The problem could be solved by electronically controlled piston sliding. The power shifter presented by us can be used where highdemands are placed on the simplicity of the overall circuitry, the accuracy of the phase shift setting, the speed of the phase shift, and where emphasis is placed on minimum power losses.

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References

[1] J. Vrba, *Měření na centimetrových vlnách: Velmi krátké vlny*, SNTL Praha, 1958 (in Czech).

[2] Q. Zhang, C. Yuan, and L. Liu, "Studies on mechanical tunable waveguide phase shifters for phased-array antenna applications", *IEEE International Symposium on Phased Array Systems and Technology*, Waltham, MA, USA, ISBN 978-1-5090-1448-4, 2016.

[3] Q. Zhuang, F. Yan, Z. Jiang, M. Liu, Z. Xiong, and C. Yan, "Study and Design of A Contracting Waveguide Phase Shifter for S-band High-Power Microwave Applications", *International Conference on Electronics Technology* (ICET), Chengdu, China, ISBN 978-1-7281-1619-8, 2019.

[4] W. P. A. Clark, "High-Power Phase Shifter for Phased Array Systems", *G-MTT International Symposium, Clearwater*, FL, USA, Date Added to IEEE Xplore: 06 January 2003, 1965.

[5] H. I. Altan, O. A. Civi, and S. Demir, "X-Band high power ferrite phase shifter", *Mediterrannean Microwave Symposium (MMS)*, Guzelyurt, Northern Cyprus, ISBN 978-1-4244-7243-7, 2010.

[6] G. J. Deng, W. H. Huang, J. W. Li, H. Shao, T. Ba, L. T. Guo, and S. Y. Xie, "Theoretical and Experimental Comparative Analysis Between Double-toroid and Quadruple-slab Ferrite Phase Shifters", *International Conference on Microwave and Millimeter Wave Technology Proceedings*, Guangzhou, China, ISBN: 978-1-7281-2169-7, 2020.

[7] D. A. Ellerbruch, "UHF and microwave phase-shift measurements", *Proceedings of the IEEE*, vol. 55, no. 6, pp. 960-969, 1967.

[8] K. Molz, N. Pribble, and B. Dodson, "A review of microwave phase shifters", *Microwaves*, vol. 3, pp. 80-83, 1964.

[9] J. Helszajn, *Microwave Polarizers, Power Dividers, Phase Shifters, Circulators and Switches*, Wiley IEEE Press, New York, USA, , ISBN 9781119490050.

[10] S. C. Bera, *Microwave Active Devices and Circuits for Communication*, Springer Singapore, Singapore, ISBN 978-981-13-3003-2, 2019.

[11] J. Choma and W. K. Chen, *Feedback networks: theory and circuit applications*, World Scientific, Singapore, ISBN 978-981-02-2770-8, 2007.

[12] P. J. Pupalaikis, *S-Parameters for Signal Integrity*, Cambridge University Press, UK, ISBN 9781108489966, 2020.

[13] W. R. Eisenstadt, B. Stengel, and B. M. Thompson, *Microwave Circuit Design Using Mixed Mode S-Parameters*, GreatBookPrices, Columbia, MD, USA, ISBN 9781580539333, 2009.

[14] K. Kurokawa, "Power Waves and the Scattering Matrix", *IEEE Trans. Micr. Theory& Tech*, doi 10.1109/TMTT..1125964, 1965.

[15] R. E. Collin, *Foundations For Microwave Engineering*, Second Edition, Wiley-IEEE Press, New Jersey, USA, ISBN 9780780360 310, 2000.

[16] R. N. s. p. Mavaddat, *World Scientific*, Singapore, ISBN 978-981 -02-2305-2, 1996.

[17] L. Yongguang, M. Ru, and Z. Qi, *Investigation of X-band Digital High-Power Circulator-Based Phase Shifter*, Antennas and Propagation Society International Symposium, Fajardo, PR, USA, ISBN 978-1-5090-2886-3, 2016.

[18] D. L. Dražan, K. R. Križan, and P. M. Popela, "Design and Testing of a Low-Tech DEW Generator for Determining Electromagnetic Immunity of Standard Electronic Circuits", *Energies*, 14(11), 3090, ISSN 1996-1073, 2021.

[19] K. R. Križan and D. L. Dražan, "Microwave Generator", *International Conference on Military Technology Proceeding, ICMT15*, . Brno University of Defense, pp. 531-535. ISBN 978-80-7231-976-3, 2015.

[20] Boonton Electronics > Products > RF Power Sensors > RTP5000 Real-Time Peak Power Sensors. Boonton Electronics, https://www.boonton. com/products/rf-power-sensors/rtp 5000-real-time-peak-power-sensors.

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