Antenna Structures for Emerging Frequency Bands

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Abstract — **In the paper, the design of Vivaldi antennas operating in Ka band and W band of millimeter waves is described. Attention is turned to the impedance bandwidth of the antennas. Discussions are focused on the transition of the design in the Ka band to the design in the W band. The designs are supported by simulations in CST Microwave Studio and compared with measurements.**

Keywords — **Ka band, K connector, W band, Vivaldi antenna, W connector.**

I. Introduction

Today's wireless communication suffers from the lack of free frequency spectrum. Therefore, communication systems are shifted to higher and higher frequency bands. At higher frequencies, novel design techniques of communication components have to be exploited.

In the paper, the design of Vivaldi antenna operating in Ka band (26.5 GHz to 40.0 GHz) is reviewed [1], [2], [3]. Then, the transition of the design to the bands V (50 GHz to 70 GHz), E (60 GHz to 90 GHz) and W (75 GHz to 110 GHz) is discussed.

The basic design procedure of Vivaldi antenna is reviewed in Section 2. In Section 3, the antenna design in the Ka band is explained. Sections 4 and 5 show the transition to the W band.

II. Vivaldi Antenna Design

Vivaldi antenna is a member of a class of aperiodic continuously scaled traveling-wave antennas. Vivaldi antenna is created by an exponential slot in a conductive layer. The conductive layer forms the top side of the dielectric substrate. A proper operation of the antenna is conditioned by the validity of the relation [1]:

$$\frac{h_{ef}}{\lambda} = \left(\sqrt{\varepsilon_r} - 1\right)\frac{h}{\lambda_0}, \tag{1}$$

where ε_r is the dielectric constant of the microwave substrate, h is the height of the substrate, λ_0 is the wavelength in free space, and h_{ef} is the effective height of the substrate. The effective height should vary within the interval 0.005 – 0.030 of the wavelength for the antennas of the length L [1]

$$3\lambda \le L \le 8\lambda, \tag{2}$$

where L is the physical length of the exponential part of the antenna.

The radiated electromagnetic wave is linearly polarized, and oriented in parallel to the aperture edge of the substrate [1].

Geometry of Vivaldi antenna can be determined by the following considerations.

The lowest operation frequency f_d is determined by the width of the aperture edge, and the length of the exponential slot [2]

$$W = L = R_{S1} = \frac{c}{f_d}\sqrt{\frac{2}{\varepsilon_r + 1}}, \tag{3}$$

where c is the velocity of light, ε_r is the dielectric constant of the substrate, and f_d is the lowest operation frequency.

The width of the microstrip feeder of the characteristic impedance Z_0 is given by [2]

$$W_m = \frac{120\pi}{\sqrt{\varepsilon_r}}\frac{h}{Z_0}, \tag{4}$$

where h is the height of the substrate and Z_0 is the required characteristic impedance.

Arms of Vivaldi antenna are of the shape of ellipses with radii R_1, R_2 and radii R_{S1}, R_{S2}. The radii can be evaluated according to [2]

$$R_1 = \frac{W}{2} + \frac{W_m}{2}, \tag{5}$$

$$R_2 = \frac{W}{2} - \frac{W_m}{2}, \tag{6}$$

$$R_{S1} = L = W, \tag{7}$$

$$R_{S2} = 0.5R_2, \tag{8}$$

where W_m is the width of the microstrip feeder given by the equation (4).

Finally, the antenna structure has to be completed by the matching circuitry. The matching circuitry (the impedance transformer) is a part of the transition from the non-symmetric transmission line to the symmetric one [4].

Fig. 1 shows the basic geometry of the antenna indicating the design dimensions.

III. Vivaldi Antenna for Ka Band

Vivaldi antenna was designed and implemented on the microwave substrate ARLON 25N (height h = 0.788 mm,

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dielectric constant $\varepsilon_r = 3.24$, loss factor $\tan\delta = 0.0025$ at $f = 10$ GHz). Fig. 2 shows the geometry of the final design of Vivaldi antenna.

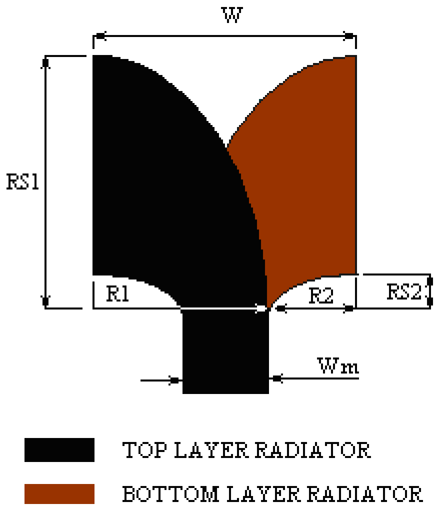

Fig. 1. Vivaldi antenna: the basic geometry.

Vivaldi antenna for Ka band operation is of the following dimensions: $W_1 = 10.140$ mm, $W_2 = 3.240$ mm, $W_3 = 1.816$ mm, $W_4 = 4.490$ mm, $W_5 = 12.712$ mm, $L = 10.140$ mm, $L_1 = 1.511$ mm, $L_2 = 0.900$ mm, $L_3 = 2.987$ mm, $L_4 = 15.538$ mm, $R_1 = 6.690$ mm, $R_2 = 3.450$ mm, $R_{S1} = 10.140$ mm, and $R_{S2} = 1.720$ mm.

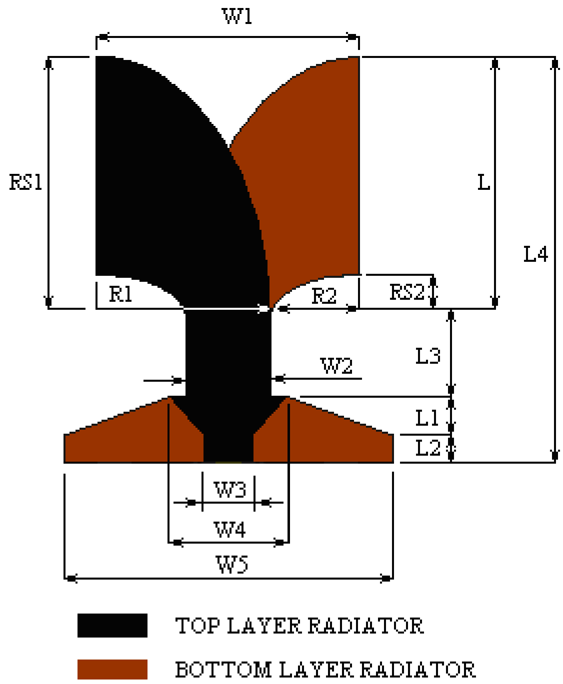

Fig. 2. Vivaldi antenna: geometry of Ka band implementation.

The transition from the balanced twin-line to a coaxial unbalanced feed point is implemented using a linear microstrip taper. The unbalanced end of the tapered balun resembles a microstrip line of width W_3 ($Z = 50\ \Omega$) over a finite ground plane of width W_5. In order to approximate an ideal microstrip line, the ground plane has to be much wider than the metallic strip. In the proposed design, a ratio $W_5 / W_3 = 7$ is assumed [4]. In this design, the width W_4 depends on the opening angle of the strip, and equals to $a = 6^\circ$ [4]. The length $L_1 = 0.303\ \lambda_g$ [4] and the length $L_3 = 0.600\ \lambda_g$ [4]. Here, λ_g is the wavelength on the microwave substrate given by

$$\lambda_g = \frac{\lambda_0}{\sqrt{\varepsilon_{ef}}}, \tag{9}$$

where λ_0 is free-space wavelength, and ε_{ef} is effective permittivity of the microwave substrate. Fig. 3 shows the geometry of the numerical model of Vivaldi antenna, which is fixed to the K connector (2.92 mm). The numerical model of the antenna structure was developed in CST Microwave Studio. Electromagnetic analysis of the antenna structure was performed by the transient solver.

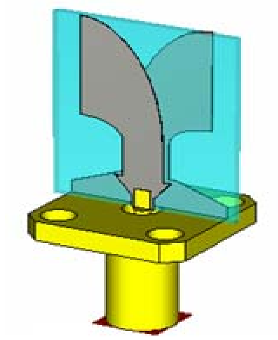

Fig. 3. Geometry of CST model of Ka-band Vivaldi antenna fixed to K connector.

In Fig. 4, computed and measured frequency responses of the reflection coefficient at the antenna input are compared. The bandwidth was reduced due to losses and parasitic properties of the 2.92 mm connector.

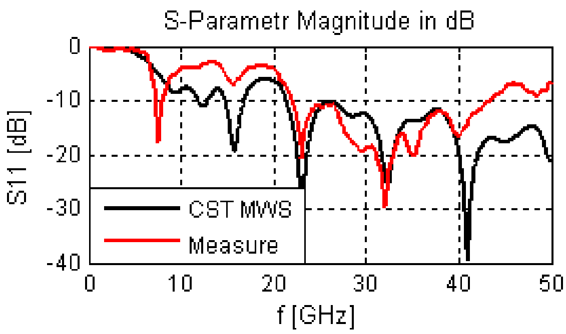

Fig. 4. Frequency response of the reflection coefficient at the input of Ka-band Vivaldi antenna.

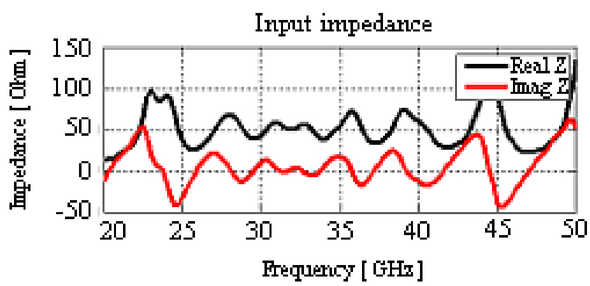

Fig. 5. Measured frequency response of input impedance of Vivaldi antenna: input resistance (black) and input reactance (red).

The bandwidth defined by the –10 dB decrease of the magnitude of the reflection coefficient at the input of the measured antenna is B = 22.43 GHz. The real component and the imaginary one of the input impedance are shown in Fig. 5.

Measured and computed directivity patterns of the Vivaldi antenna are depicted in Fig. 6.

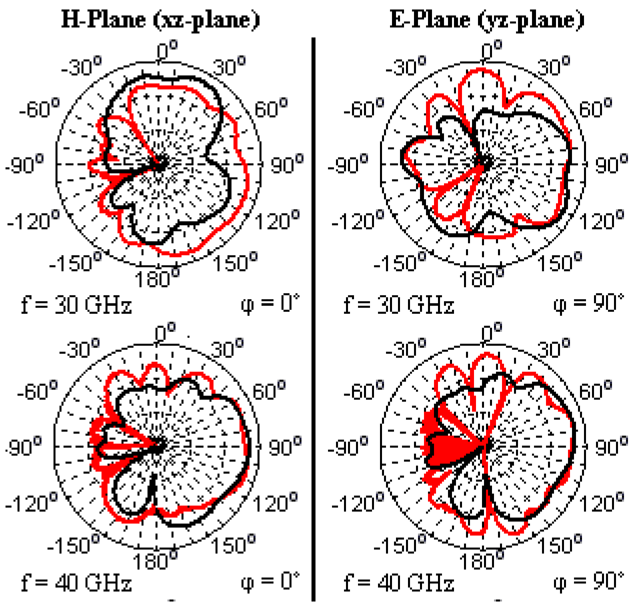

Fig. 6. Measured (red) and computed (black) directivity patterns of the Vivaldi antenna: H plane (left) and E plane (right).

IV. W CONNECTOR AND SILICON SUBSTRATE

Increasing frequency, conventional microwave substrates have been loosing required properties and losses have been increasing [6]. Therefore, conventional substrates have to be replaced by highly-resistive silicon.

Moreover, a proper connector and its fixing to the antenna have to be carefully chosen. From the viewpoint of wide impedance bandwidth, exploitation of W connector seems to be a promising solution: the theoretical bandwidth of such solution is 0 to 135.7 GHz [5]. Practically, the bandwidth is limited by 110 GHz. Dimensions of W-connectors are recommended by IEEE Std. 287-2007.

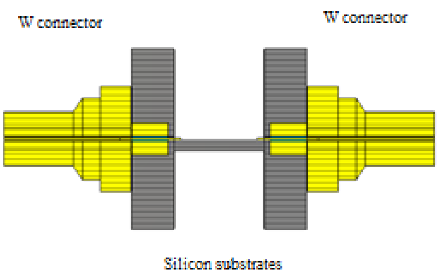

Fig. 7. Geometry of the CST model of W-connector.

In order to develop as accurate computer model of the W connector as possible, most parasitic properties of the modeled structure have to be considered. Fig. 7 shows the geometry of the CST model of two W connectors (Anritsu W1-103F), which are connected by the microstrip transmission line of the characteristic impedance Z_0 = 50 Ω. Used silicon substrate is of the following parameters: height h = 0.1 mm, dielectric constant ε_r = 11.8, and resistivity ρ = 7 kΩm.

Frequency response of the reflection coefficient at the input S_{11} and the transmission of the structure S_{21} are shown in Fig. 8 and Fig. 9.

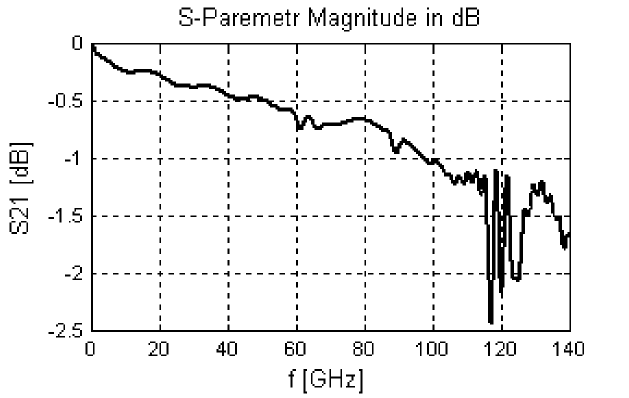

Fig. 8. Frequency response of the transmission coefficient of the microstrip line completed by W-connectors.

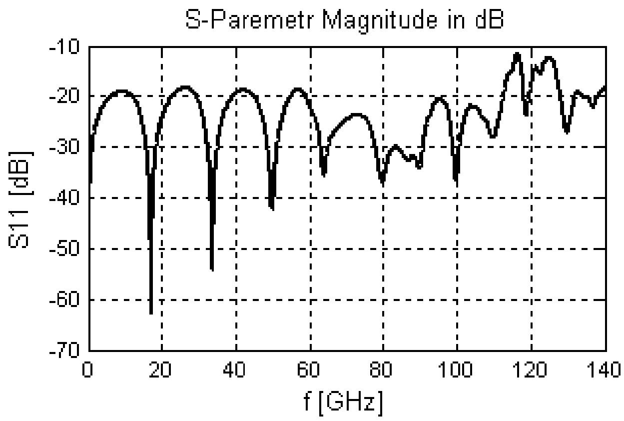

Fig. 9. Frequency response of the reflection coefficient of the microstrip line completed by W-connectors.

A proper connection of the microstrip transmission line to the connector is of a high importance.

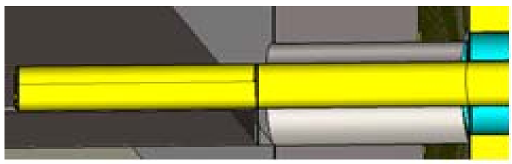

Fig. 10. Detail of microstrip to W-connector transition.

A recommended offset and the dimension of the compensation gap have to be respected. Fig. 10 shows the detail of the connection between the microstrip and the connector manufactured by Anritsu.

V. VIVALDI ANTENNA FOR W BAND

Vivaldi antenna is designed considering high-resistivity silicon substrate (height h = 0.1 mm, permittivity ε_r = 11.8 and resistivity ρ = 7 kΩm). Layout of the antenna is shown in Fig. 11.

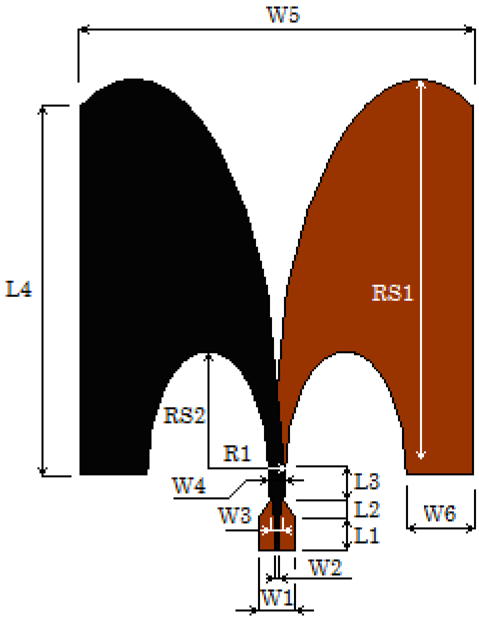

Fig. 11. Layout of W-band Vivaldi antenna.

W-band Vivaldi antenna is of the following dimensions: W_1 = 0.4774 mm, W_2 = 0.0682 mm, W_3 = 0.1230 mm, W_4 = 0.1976 mm, W_5 = 4.9643 mm, W_6 = 0.8487 mm, L_1 = 0.3670 mm, L_2 = 0.2692 mm, L_3 = 0.2936 mm, L_4 = 4.6187 mm, R_{S2} = 1.5431 mm, R_1 = 1.8892 mm, and R_{S1} = 4.9634 mm.

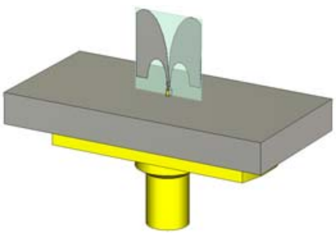

Fig. 12. Geometry of the numerical model of W-band Vivaldi antenna developed in CST.

Fig. 13 shows frequency response of the magnitude of the reflection coefficient at the input of the W-band Vivaldi antenna. The impedance bandwidth of the antenna is 65 GHz. Real and imaginary parts of the input impedance of the antenna are depicted in Fig. 14.

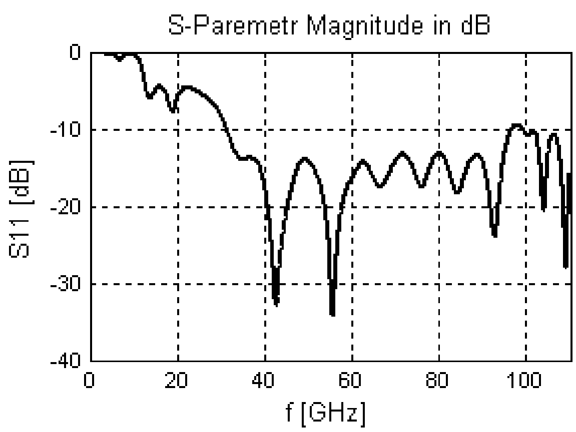

Fig. 13. Frequency response of the reflection coefficient at the input of W-band Vivaldi antenna.

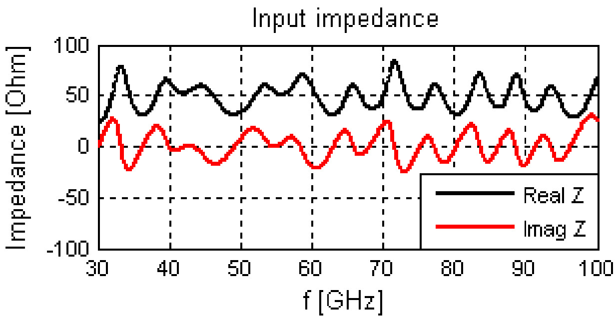

Fig. 14. Input impedance of W-band Vivaldi antenna: input resistance (black), and input reactance (red).

Fig. 15 shows directivity patterns of the W-band Vivaldi antenna computed in CST Microwave Studio for frequencies f_1 = 71 GHz and f_2 = 76 GHz.

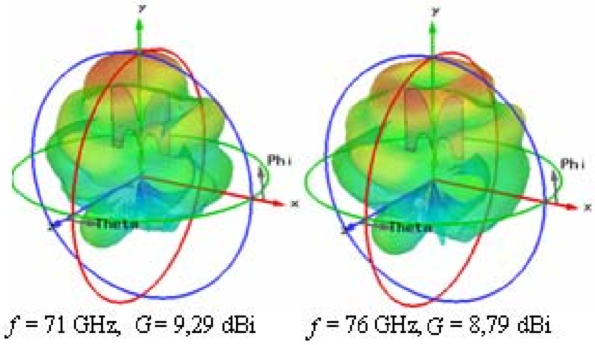

Fig. 15. Directivity patterns of the W-band Vivaldi antenna at f_1 = 71 GHz (left) and f_2 = 76 GHz (right).

VI. Conclusion

In the paper, practical implementation of a wideband antenna for frequencies 71 GHz to 76 GHz is described. The antenna is designed for the high-resistivity silicon substrate. The impedance bandwidth of the designed antenna is B = 65 GHz (compared to 22.4 GHz of the Ka-band antenna).

Experimental verification of technical parameters of the W-band Vivaldi antenna is under preparation.

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