Passive Millimeter-Wave Imaging Using Substrate Integrated Waveguide Technology

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Abstract—**A Passive Millimeter-Wave Imaging System for concealed object detection at the frequency of 24 GHz with total power radiometer configuration has been designed and tested. We added to the system a microwave lens to focus the target under surveillance to the antenna. The novelty of this work is the incorporation of the Substrate Integrated Waveguide (SIW) Flare Horn Antenna**.

***Index Terms*—microwave lens, nipkow disc, passive millimeter-wave imaging, radiometer, substrate integrated waveguide antenna.**

I. Introduction

THE NEED for a concealed weapons and explosive detection has increased in recent years. The Millimeter-Wave (MMW) Imaging is a possible solution to this problem since millimeter-waves can penetrate thin clothing layers. This is a method of forming images through the detection of millimeter-wave radiation from a scene. This power is a combination of what the scene object is directly emitting and what it is reflecting from its environment. The MMW radiation does not present a health hazard to people under surveillance and this kind of systems has also the ability to see under conditions of low visibility (fog, clouds, smoke, sandstorms, etc.) that would ordinarily blind visible or infrared (IR) sensors [1], [2].

Millimeter-wave Imaging can be either active or passive [3]. In active mode a source illuminates the scene, which could be non-coherent or coherent, monochromatic or broadband. The source produces much higher power than those emitted from blackbodies within the scene (typically tens of thousands of degrees). Due to the much higher effective temperature of the surroundings, the millimeter waves generated by objects between the scene are of less significance producing more contrast in the imaging results but also undesired speckle and/or glint. In Passive Millimeter-Wave (PMMW) Imaging, the spectral distribution of natural radiation which is emitted or reflected from a body at environmental temperatures is properly captured and displayed (radiometry). Here we have less contrast that in the active mode but better image quality.

Various active and passive mode millimeter-wave imaging systems for target identification have been documented by several authors [1]-[15]. However, there is no report of a PMMW Imaging System using substrate integrated waveguide technology in the receiver antenna.

The novelty of this work is the incorporation of the Substrate Integrated Waveguide (SIW) Technology in the receiver antenna of the PMMW Imaging System. The SIW Technology is synthesized by placing two rows of metallic via-holes in a substrate. The field distribution in an SIW is similar to that in a conventional rectangular waveguide. Hence, it takes the advantages of low cost, lower losses than coplanar and microstrip lines, and it is highly integrable with microwave and millimeter wave integrated circuits [16]-[19].

II. Total Power Radiometer

A radiometer is a sensitive receiver specially designed to measure the radiation that a body either emits directly or reflects from surrounding bodies [20], [21].

The aspect of radiometry that is of most interest to the microwave engineer is the design of the radiometer itself. The basic problem is to build a receiver that can distinguish between the desired radiometric noise and the inherent noise of the receiver, even though the radiometric power is usually less than the receiver noise power. The total power radiometer configuration represents an approach to this problem.

The block diagram of a typical total power radiometer is show in Fig. 1 [22], [23]. The front end of the receiver is a standard superheterodyne circuit consisting of an RF amplifier, a mixer/local oscillator, and a detector stage. This detector is generally a square-law device, so that its output voltage is proportional to the input power. The integrator is essentially a low-pass filter with a cutoff frequency of $1/\tau$, and serves to smooth out short-term variations in the noise power [24].

If the antenna is pointed at a background scene with a brightness temperature T_B, the antenna power will be $P_A=kT_BB$; this is the desired signal. The receiver contributes noise which can be characterized as a power $P_R=kT_RB$ at the receiver input, where T_R is the overall noise temperature of

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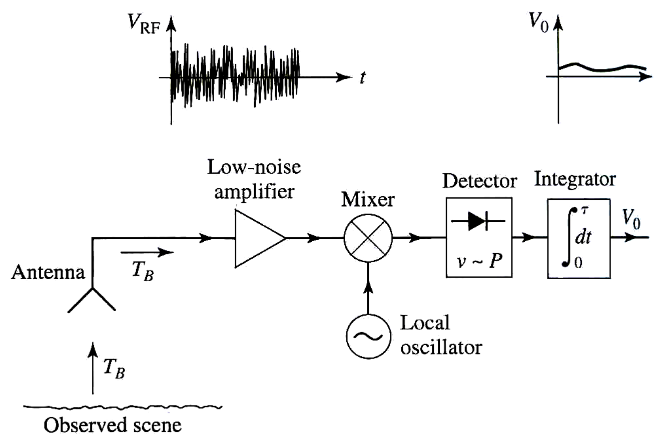

Fig. 1. Total Power Radiometer block diagram.

the receiver. Thus the output voltage of the radiometer is

$$Vo = G(T_B + T_R)kB \tag{1}$$

where G is the overall gain constant of the radiometer.

III. Passive Millimeter-Wave Imaging System

The experimental arrangement constructed for the passive millimeter wave imaging system is shown in Fig. 2. This system works at the frequency of 24 GHz. For the electronics we used the total power radiometer configuration described in section II.

To detect the small radiation emitted by the target we use a LNA which has a bandwidth from 15 to 26 GHz, 2.8 dB NF and 55 dB gain. To downconvert the frequency we use a triple balanced mixer with 9.5 dB NF. The local oscillator used achieves output power from 13 to 16 dBm with phase noise of ~135 dBc/Hz, and approximately 1 GHz of tuning range. The detector used is a square law detector with bandwidth from DC to 40 GHz. As mentioned in section II, an integrator with an integration time of 3 milliseconds was implemented to increase the sensitivity of the system.

We added to the system a microwave lens [25] to focus the target under surveillance to the antenna. The lens used has a diameter of 24 cm and it is made of Teflon material.

We designed a SIW horn antenna as proposed in reference [26]. We modified the design of the antenna by introducing exponential flares to have a wide bandwidth as shown in Fig. 3. The dimensions of the microstrip line are W_2 =3.8mm, and L_2 =2mm. The transition (from microstrip to SIW) dimensions are W_3 =5.32mm, and L_3 =10mm. The SIW dimensions are W_4 =6.312mm, L_4 =3.4mm, cylinder radius r =0.5mm, and cylinder separation p =1.2mm. The substrate thickness is h =2mm, and dielectric constant ε_r =10.2. The radius lens is H=8.6mm. The overall dimensions of the horn antenna are 41.775 x 19.4 x 2 mm^3.

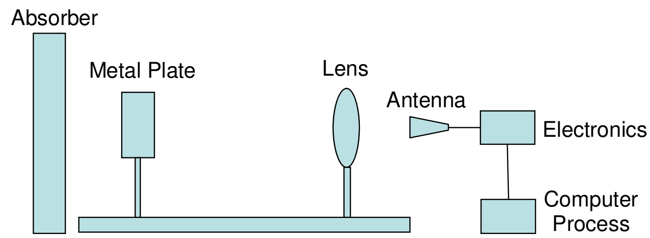

Fig. 2. Passive Millimeter-wave Imaging System block diagram.

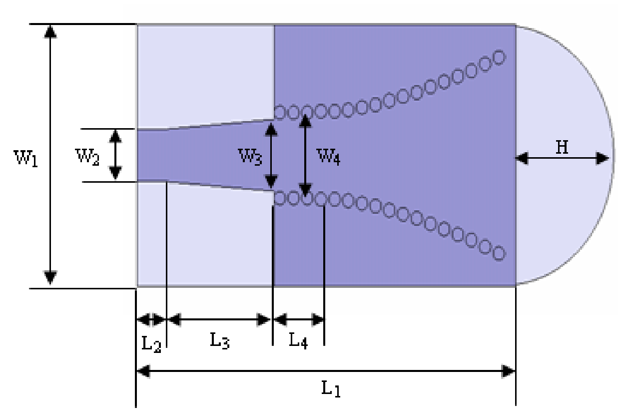

Fig. 3. Geometry of the SIW exponential flare horn antenna. The dimensions of the microstrip line are W_2 =3.8mm, and L_2 =2mm. The transition dimensions are L_3 =10mm, and W_3 =5.32mm. The SIW dimensions are W_4 =6.312mm, L_4 =3.4mm, cylinder radius r =0.5mm, and cylinder separation p =1.2mm. The substrate thickness is h =2mm, and dielectric constant of ε_r =10.2. The overall dimensions of the horn antenna are 41.775 x 19.4 x 2 mm^3.

Object	Voltage (mV)
Initial Voltage	81
Aluminum Metal Plate	110
Plastic Plate	79
Plastic Mousepath	78
Plastic Bucket	77
Plastic Mobile	79
Ceramic Plate	70
Cardboard Plate	81

Table 1. Voltage of different materials under surveillance

IV. Results

To demonstrate the sensitivity of our system, several tests have been performed with concealed objects of different materials such as plastics, ceramics, cardboard and aluminum. The obtained results, measured at room temperature, are shown in Table 1. The initial output voltage at the detector of our system having a microwave absorbing background foam 1m from the antenna was 81 mV. Then different objects have been sensed by placing them between the microwave foam wall and the receiver antenna. The metal plate shows the greatest voltage change with a difference of approximately 30 mV, while the cardboard plate did not provide any change. These findings are consistent with the theory, since the metal plate has an emissivity near to zero [11] and the cardboard is invisible to the millimeter waves [3].

The SIW antenna was simulated using a commercial finite element method package [26], and then fabricated. Its bandwidth is from 18 to 40 GHz, having a good response of the return loss S_{11} (under -10 dB approximately, see Fig. 4). The arc lens placed in the substrate improves the directivity of the SIW antenna. The radiation pattern obtained is illustrated in Fig. 5.

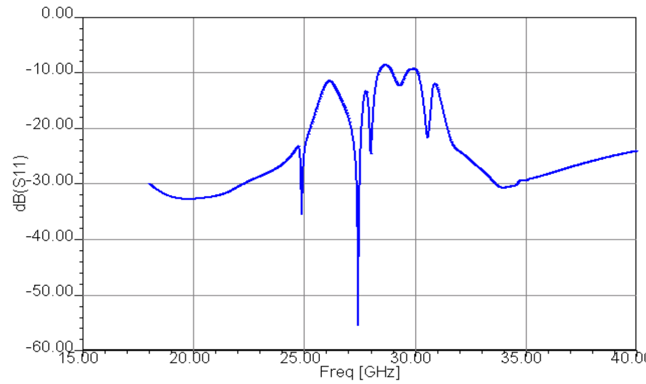

Fig.4. Return Loss S_{11} of the SIW exponential flare horn antenna.

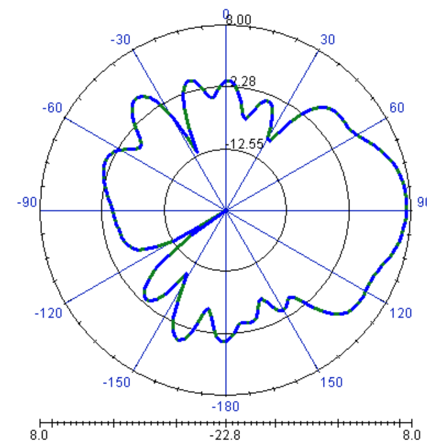

Fig. 5. Radiation patterns of the SIW exponential flare horn antenna.

V. Conclusions

A passive millimeter-wave imaging system using SIW technology has been shown, different materials such as plastics, ceramics, cardboard and aluminum have been successfully detected. The incorporation of the SIW Technology in the radiometer of the PMMW Imaging System allows cost reduction and high integrability millimeter wave integrated circuits.

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References

[1] L. Yujiri, M. Shoucri, and P. Moffa, “Passive millimeter wave imaging,” *IEEE Microwave Magazine*, vol. 4, no. 3, pp. 39-50, Sep. 2003.
[2] M. Shoucri, R. Davidheiser, B. Hauss, P. Lee, M. Mussetto, S. Young, and L. Yujiri, “A Passive Millimeter Wave Camera for Aircraft Landing in Low Visibility Conditions,” *Aerospace and Electronic Systems Magazine, IEEE*, vol. 10, no. 5, pp. 37-42, May 1995.
[3] J. Detlefsen, A. Dallinger, and S. Schelkshorn, “Approaches to Millimeter-Wave Imaging of Humans**,”** *Radar Conference, 2004. EURAD. First European***,** 2004, pp. 279-282.
[4] K. Mizuno, H. Matono, Y. Wagatsuma, H. Warashina, H. Sato, S. Miyanaga, and Y. Yamanaka, “New Applications of Millimeter-Wave Incoherent Imaging,” *Microwave Symposium Digest, 2005 IEEE MTT-S International,* 12-17 June 2005, pp. 629-632.
[5] L. L. Chao, Y. Jianyu, Z. Xin, F. Yong, and Z. R. Hong, “Design of a PMMW Imaging system,” *Communications, Circuits and Systems, 2007. ICCCAS 2007. International Conference*, 11-13 July 2007, pp. 1313-1316.
[6] G.N. Sinclair, R.N. Anderton, and R. Appleby, “Outdoor passive millimetre wave security screening,” *Security Technology, 2001 IEEE 35th International Carnahan Conference*, 16-19 Oct. 2001, pp. 172-179.
[7] D.O. Korneev, L. Y. Bogdanov, and A.V. Nalivkin, **“**Passive Millimeter Wave Imaging System with White Noise Illumination for Concealed Weapons Detection,**”** *Infrared and Millimeter Waves, 2004 and 12th International Conference on Terahertz Electronics, 2004. Conference Digest of the 2004 Joint 29th International Conference*, 27 Sept.-1 Oct. 2004, pp. 741-742.
[8] K. Watabe K. Shimizu, M. Yoneyama, and K. Mizuno, “Millimeter-Wave Active Imaging Using Neural Networks for Signal Processing,” *Microwave Theory and Techniques, IEEE Transactions*, vol. 51, no. 5, pp. 1512-1516, May 2003.
[9] I.. Ocket, B. Nauwelaers, G. Koers,and J. Stiens, “Fast Modeling and Optimization of Active Millimeter Wave Imaging Systems,” *Microwave Conference, 2006. 36th European*, Sept. 2006, pp. 1559-1562.
[10] T. Derham, H. Kamoda, T. Iwasaki, and T. Kuki, “Active MMW Imaging System using the Frequency-Encoding Technique,” *Microwave Conference, 2007. KJMW 2007. Korea-Japan*, 15-16 Nov. 2007, pp. 181-184.
[11] L. Yujiri, “Passive Millimeter Wave Imaging,” *Microwave Symposium Digest, 2006. IEEE MTT-S International*, pp. 98-101, June 2006.
[12] V.E. Lyubchenko, “Millimeter Wave Imaging Systems,” *Microwaves Radar and Wireless Communications. 2000. MIKON-2000. 13th International Conference*, 22-24 May 2000, vol. 3, pp. 63-69.
[13] D.L. McMakin, D.M. Sheen, and T.E. Hall, “Three-Dimensional Millimeter-wave Imaging for Concealed Weapon Detection,” *Microwave Theory and Techniques, IEEE Transactions*, vol. 49, no. 9, pp. 1581-1592, Sep. 2001.
[14] D.L. McMakin, D.M. Sheen, and H.D. Collins, “Remote Concealed Weapons and Explosive Detection on People Using Millimeter-wave Holography,” *Security Technology, 1996. 30th Annual 1996 International Carnahan Conference*, 2-4 Oct. 1996, pp. 19-25.
[15] Z. Luo, J. Xiong, and J. Yang, **“**An Image Regulation Technique for Passive Millimeter Wave Focal Plane Array Imaging Radar System,**”** *Radar, 2006. CIE '06. International Conference*, Oct. 2006, pp. 1-4.
[16] W. D’Orazio, and K. Wu, “Substrate-Integrated-Waveguide Circulators Suitable for Millimeter-Wave Integration,” *Microwave Theory and Techniques, IEEE Transactions*, vol. 54, no. 10, pp. 3675-3680, Oct. 2006.
[17] W. D’Orazio, K. Wu, and J. Helszajn, “A Substrate Integrated Waveguide Degree-2 Circulator,” *Microwave and Wireless Components Letters, IEEE*, vol. 14, no. 5, pp. 207 – 209, May 2004.

[18] K. Wu; D. Deslandes, and Y. Cassivi, “The Substrate Integrated Circuits - A New Concept for High-Frequency Electronics and Optoelectronics,” *Telecommunications in Modern Satellite, Cable and Broadcasting Service, 2003. TELSIKS 2003. 6th International Conference*, vol. 1, 1-3 Oct. 2003, pp. III-X
[19] W. Che, B. Yao, and Y. L. Chow, “Substrate Integrated Waveguide Horn Antenna with Dielectric Lens,” *Microwave and Optical Technology Letters*, vol 49, no. 1, pp. 168-170, Jan. 2007.
[20] D. M. Pozar, “Microwave Engineering,” 3rd ed., Ed. Wiley, 2005, pp. 665-667.
[21] F.T. Ulaby, R. K. Moore, and A. K. Fung, “Microwave Remote Sensing: Active and Passive, Volume I, Microwave Remote Sensing Fundamentals and Radiometry,” Artech House, 1981, pp. 186-187.
[22] M. E. Tiuri “Radio Astronomy Receivers,” *Antennas and Propagation, IEEE Transactions*, vol. 12, no. 7, pp. 930-938, Dec 1964.
[23] L. Quan, Z. Yong-hong, C. Qi-ke, F. Yong, Y. Jian-yu, and L. Liang-chao, “The W Band Radiometer for Imaging,**”** *Communications, Circuits and Systems, 2007. ICCCAS 2007. International Conference*, 11-13 July 2007, pp. 1306-1308.
[24] H. Kim, S. Duffy, and J. Herd, “SiGe IC- based mm-wave imager,” *Circuits and Systems, 2007. ISCAS 2007. IEEE International Symposium*, 27-30 May 2007, pp. 1975-1978.
[25] W. Chalodhorn, and D. R. DeBoer, “Use of Microwave Lenses in Phase Retrieval Microwave Holography of Reflector Antennas,” Antennas and Propagation, IEEE Transactions, vol. 50, no. 9, pp. 1274-1284, Sep 2002.
[26] *“Ansoft HFSS*, version 9,” Ansoft Corporation 2003.

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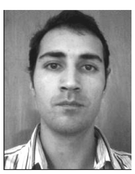

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