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PAPER

Dielectric Lens-Based Millimeter Wave Imaging for Concealed Object Detection in Security Applications

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SUMMARY To improve throughput in security inspection procedures, a millimeter-wave (mmW) imaging system with a high-throughput operation with reasonable resolution compared to conventional mmW imaging systems is developed. Investigates the distinctive attributes of mmW, including its safe penetration through clothing, the study demonstrates the generation of detailed two-dimensional reconstructions of objects. Through the strategic use of a lens, signal amplitudes and phases are effectively captured, yielding reconstruction images from the signal reflected from the target. Experimental validations further affirm the effectiveness of mmW imaging with a dielectric lens, showcasing successful reconstructions of targets positioned at the lens's front focal plane. Notably, the approach exhibits proficiency in discerning objects obscured behind non-metallic materials such as paper and cloth. These findings highlight the potential of utilizing Fourier transform analysis and a dielectric lens in mmW imaging, presenting a promising approach for security applications, particularly in the detection of concealed objects.

key words: *millimeter-wave, imaging, dielectric lens, remote sensing, security inspection.*

1. Introduction

The demand for effectively identifying potential threats and hazardous items in public security systems has increased significantly in recent years [1-2]. However, conventional security and surveillance techniques have limited utility in practice. Surveillance cameras often find it difficult to detect weapons like knives, pistols, or explosive devices concealed under the clothing of suspicious individuals [3-5]. Metal detectors may detect metal objects but cannot differentiate between threatening and non-threatening items like keys or belt buckles, often resulting in false alarms. Furthermore, it is unable to detect modern plastic-based threat objects [6-7]. X-ray devices emit ionizing radiation that can be damaging to persons and are commonly used to inspect carry-on items [8].

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A practical security checking system usually involves the integration of the mentioned methods. An airport security screening process includes using X-ray scans to examine luggage and employing metal detectors or manual techniques to detect any forbidden objects someone may be carrying. Therefore, these conventional methods necessitate individuals to queue and wait for individual inspection. Challenges arise when implementing security screening systems in crowded public spaces or buildings with numerous individuals. This procedure significantly prolongs the waiting time, hinders the effectiveness of security checks, and leads to delays in busy surroundings. Hence, it is essential to develop a security measures system that does not necessitate individuals to wait at a specific location [9-10]. Millimeter-wave (mmW) radiation, classed as non-ionizing radiation, emerges as a viable solution due to its capability to penetrate typical clothing and its safety for human exposure, giving advantages over ionizing radiations like X-rays [11-12]. The use of mmW technology is becoming a potential and innovative approach for applying harmless preventive measures to identify concealed items, enhancing security and surveillance in public spaces [13-15].

MmW imaging systems can be either passive or active based on whether an active illumination is present or not [16-17]. Passive imaging relies on temperature differences to perform imaging [18-19], while an active imaging system transmits mmW signals and measures the reflected signals from the target to generate images [20-23]. Hence, it is relatively less dependent on environmental conditions. Active imaging is suitable for security applications for long-distance imaging due to its high dynamic range and signal-to-noise ratio (SNR) [24-26]. Innovations aimed at improving the speed and accuracy of image generation are crucial to making security systems more practical and efficient in actual scenarios. Efforts are underway to address these challenges and streamline the operation of mmW imaging systems for security screening purposes. In addition, our objective is to develop a new millimeter-wave radio imaging system by utilizing a complex integral/correlation technique. In this regard, this approach enables efficient operation with a significant throughput and reasonable resolution compared to traditional millimeter-wave imaging systems [27-29].

The paper reports experimental results regarding the utilization of a dielectric lens for mmW radio imaging. The research reveals that a target object concealed by a layer of paper or clothing can be successfully recognized with reasonable resolution. Moreover, depth information of a target can be obtained by employing a mmW frequency sweep or emitting multiple frequencies. This approach facilitates the generation of a three-dimensional (3D) image of the object.

2. Millimeter-Wave Imaging Using Lens

Fourier transformation can be employed to analyze mmW imaging. In this manner, the reflected wave from the target is treated as a superposition of plane waves. A lens can serve as a Fourier transform device, facilitating intricate Fourier calculations on mmW imaging of objects. Fourier optics primarily analyzes monochromatic light or electromagnetic waves with a single frequency. These waves are characterized by complex values encompassing amplitude and phase information.

Fig. 1 shows a Fourier transform using a convex lens. The pattern at the back focal plane can be described as follows [30],

$$E(x_i, y_i) = \frac{1}{j\lambda f} e^{jk(f+d)} \times \exp\left[jk\frac{x_i^2 + y_i^2}{2f}\left(1 - \frac{d}{f}\right)\right] G\left(\frac{x_i}{\lambda f}, \frac{y_i}{\lambda f}\right) \tag{1}$$

when the object is placed at the front focal plane $d = f$, the second exponential factor equals one,

$$E(x_i, y_i) = \frac{e^{j2kf}}{j\lambda f} G\left(\frac{x_i}{\lambda f}, \frac{y_i}{\lambda f}\right). \tag{2}$$

The field distribution $G(x_i/\lambda f,\ y_i/\lambda f)$ on the observation plane is the Fourier transform of the object function $g(x_0, y_0)$ when the object is located to the front focal plane and the observation plane is positioned at the back focal plane. In addition, changing or moving the position of the object within the lens focus range can affect the reconstruction results.

3. Imaging Experiment

In terms of active mmW imaging which relies on illuminating objects with a mmW signal produced by an external source. The incident wave, whether planar or spherical, generates a scattered field through secondary sources within and on the object's surface. To obtain a visual representation of mmW signals, the imaging system measures the overall distribution of the scattered signal.

A photograph of the measurement set-up is shown in Fig. 2. The systems use an electrically controlled antenna to scan a two-dimensional aperture plane while keeping the target fixed on a platform. The receiver (Rx) antenna scans backscattered data over the observation plane via a motorized two-axis rail. A transmitter (Tx) antenna, operating as a millimeter-wave source, illuminates the target, and reflected signals travel through a lens to reach the receiver on the scanning plane. The received signal power must exceed the receiver's internal noise level to ensure data relevance. Hence, dielectric lenses collimate reflected signals and also enhance received signal intensity. Distance between transmitter and receiver or obstacles in the path can decrease received signal strength, compounded by signal spreading during transmission. Magnitude and phase information of the millimeter-wave signal reflected off the object is transmitted through a dielectric lens, sampled using an X-Y positioning stage, and the data is then analyzed to generate the reconstructed image.

The mmW source, equipped with horn antennas operating at 75-110 GHz, radiates waves to the object at an optimal angle for maximum reflection amplitude. On the receiving end, reliable imaging is expected to be achieved with small sampling sizes using a waveguide probe antenna (WR-10) as the Rx is placed on a scanning platform that moves in both the x and y directions. The target, centered on the platform and backed by microwave absorbers, prevents unwanted reflections. A dielectric lens made of PTFE or Teflon (refractive index of $n = 1.45$ at the mmW frequency) with a 250 mm diameter collimates the reflected wave. The object and antenna are positioned 600 mm in the lens's front and back focal planes. The observation plane aperture size is 240 mm × 240 mm, which is considered sufficient for analyzing

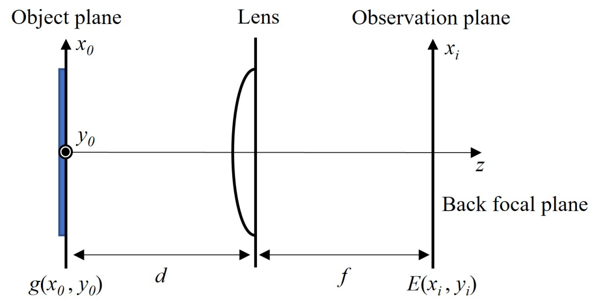

Fig. 1 Fourier transformation by lens.

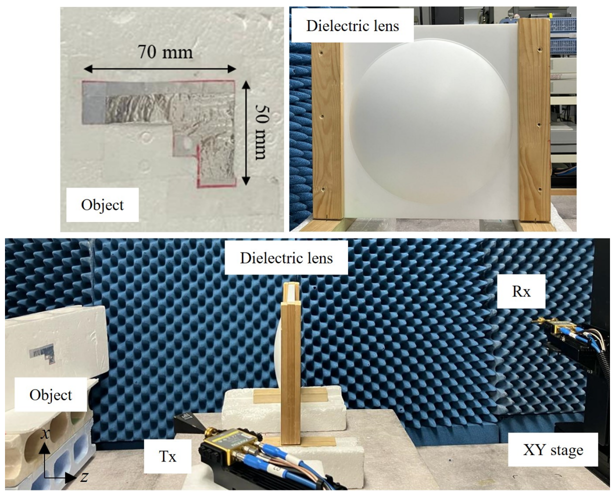

Fig. 2 Photograph of experimental setup.

collimated reflected signals from the target. To demonstrate the performance, the experiment was conducted using a flat gun-shaped object as a target. The object target was made from a general aluminum foil of 0.011 mm thickness, which is considered enough to give the amount of reflection in the W-band operation frequency. The dimension size of the object is about 70 mm × 50 mm in length and width, respectively. The collected data were analyzed to reconstruct the object image from the reflected wave of the target after passing the lens.

4. Results and Discussion

Figure 3 shows magnitude and phase profiles obtained from data gathered throughout the observation plane for the 78 GHz frequency. Experimental data was collected utilizing a 24 × 24 scanning grid arrangement with a sample interval of 10 mm and a 64 × 64 scanning grid arrangement with a sample interval of 3.75 mm. This investigation of different sample intervals was conducted to improve the resolution. The results show a comparison of the magnitude and phase patterns at the observation plane for 78 GHz using measurements of 24 × 24 points and 64 × 64 points, respectively. Increasing the sampling or the number of measurement points can lead to improved resolution, as demonstrated by the smoother pattern obtained compared to less sampling. However, it should be noted that increasing the sampling point will cause the measurement to take longer to complete. Moreover, the results show that the system effectively captures both the amplitude and phase of the signal.

The next step is to generate the reconstructed image. The magnitude and phase data obtained across the observation plane were combined and converted into complex values for reconstruction purposes. By applying the Fast Fourier Transform (FFT) to the measured mmW signal at the observation plane, the image of the target object can be effectively reconstructed. Fig. 4 shows the intensity of the acquired data after processing, demonstrating the successful reconstruction of target images by analyzing millimeter-wave signals reflected from the target. Utilizing a dielectric lens configured for Fourier imaging, a 2-dimensional image can be generated by simply performing an FFT on the collected data from the observation plane. The results coincide with the theory presented in the preceding section. A comparison of the reconstructed images of measurements for scan step intervals of 10 mm and 3.75 mm at frequencies of 78 GHz and 96 GHz can be seen in the figure. As anticipated, increasing the sampling size can result in higher resolution for the reconstructed images. Moreover, the utilization of higher frequencies can also lead to an improvement in resolution.

Several conditions were tested to demonstrate this approach as a security application. Target covers are utilized. A sheet of paper and a shirt were employed as a general cover for concealing a thing. Fig. 5 shows the reconstructed images of the objects concealed by the cover when operating at a frequency of 78 GHz and 96 GHz. The results indicate that the object image was successfully detected for recognition regardless of whether it was covered. Clear reconstruction images were obtained when no cover was present in front of the object. However, when objects were covered, the cover material reduced the reflection amplitude, resulting in slightly blurred or reduced intensity reconstructed images. Despite this, the objects remained recognizable in shape. These findings reveal the potential to detect hidden objects, which conventional methods may not achieve. Moreover, the study demonstrated that even with thin materials like aluminum foil, reconstructed images could be generated.

The received signal intensity of the imaging system was also measured. The measurement results for the received signals where Rx is fixed at the center point of the observation plane are illustrated in Fig 6. The figure shows that utilizing the lens can enhance the received signal intensity by around 10 dB while placing covers such as paper and a shirt in front

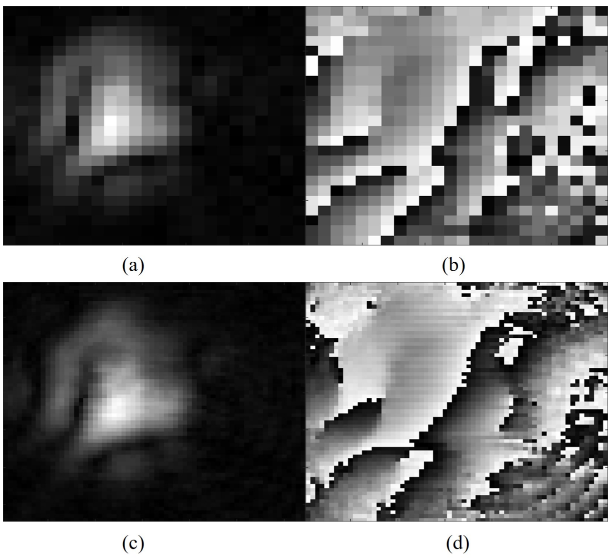

Fig. 3 Magnitude (a) (c) and phase (b) (d) comparison for 24×24 and 64×64 measurement points at 78 GHz.

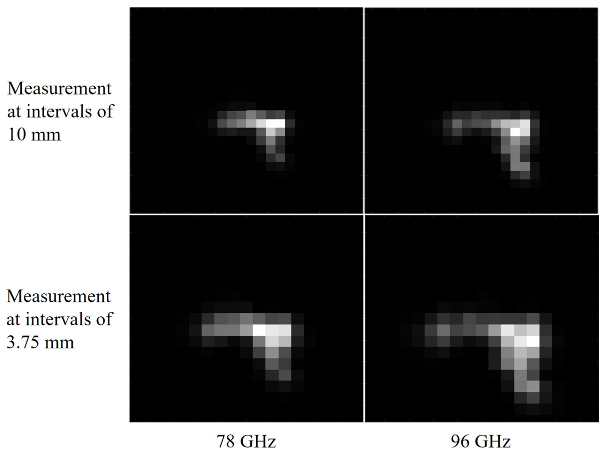

Fig. 4 Imaging results for 24×24 and 64×64 measurement points at 78 GHz and 96 GHz.

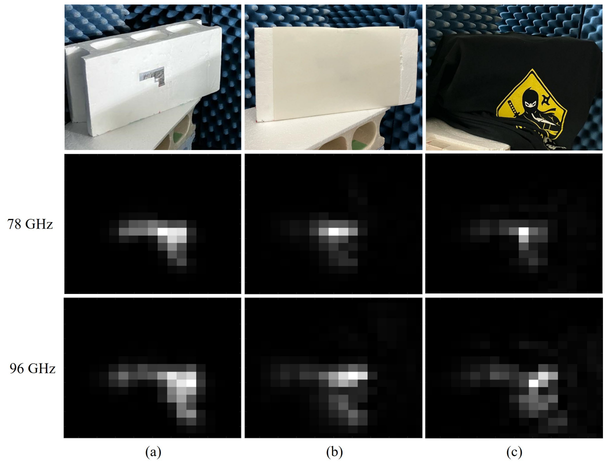

Fig. 5 Reconstructed image for different cover at a measurement interval of 3.75mm (a) no cover, (b) piece of paper, (c) a shirt.

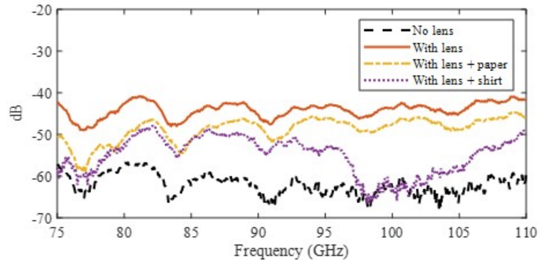

Fig. 6 Received signal intensity.

of the object reduces the signal but still maintains a relatively satisfactory level of the received signal from 75-110 GHz. There is a notable decrease in signal strength for objects covered by shirt around the 98 GHz frequency. This could be attributed to the material used for painting on the shirt. The degradation observed in the reconstructed images of the paper and shirt covered, as shown in Fig. 5, can be attributed to the lower signal level affecting the clarity of the images. Therefore, utilizing a lens is rather effective to improve the signal level, potentially enhancing the overall image quality.

The results show that the basic performance of mmW imaging was conducted. Moreover, the imaging system is also capable of producing images of three-dimensional (3D) information through either a mmW frequency sweep or the emission of multiple frequencies, which are currently being investigated. However, the raster scan approach employed in the experiment is relatively time-consuming due to limitations in the stage motor and data acquisition on the Vector Network Analyzer (VNA). Therefore, the use of a 2-D antenna array for data reception, which can be completed within a few seconds, would be ideal as it eliminates the need for moving parts, making it a favorable option for future consideration. Nevertheless, at this point, a raster scan utilizing a single antenna offers the advantage of producing high-quality reconstructed images. Furthermore, employing a single antenna for scanning helps minimize interference resulting from reciprocal interaction among array components in a multi-antenna receiving system.

5. Conclusion

The paper reported on a mmW imaging system incorporating a dielectric lens and its basic characteristics, such as its broadband functionality and signal strength. This approach facilitates imaging objects within opaque materials at various frequencies and enables comprehensive inspection such as 3D imaging. A setup involving multiple dielectric lenses to magnify the target size is underway.

Imaging using electromagnetic waves in the THz frequency range can be used for security purposes due to its better resolution. However, privacy concerns must be addressed when using this technology in public spaces. An interesting approach involves combining laser display technologies to create and project a 3D image using data obtained from the mmW imaging technique also can be employed.

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References

[1] K. Yu et al., "Design and performance evaluation of an AI-based W-band suspicious object detection system for moving persons in the IoT paradigm," in IEEE Access, vol. 8, pp. 81378-81393, 2020. DOI: 10.1109/ACCESS.2020.2991225.

[2] S. Hu, C. Shu, Y. Alfadhl and X. Chen, "W band imaging system using linear sparse periodic antenna array and compressive sensing for personnel screening," in IEEE Access, vol. 7, pp. 173603-173611, 2019. DOI: 10.1109/ACCESS.2019.2956630.

[3] Ingle. PY and Kim. YG, "Real-time abnormal object detection for video surveillance in smart cities," Sensors 22, no. 10: 3862, 2022. DOI: 10.3390/s22103862.

[4] M. Ghazal, N. Waisi, and N. Abdullah, "The detection of handguns from live-video in real-time based on deep learning," TELKOMNIKA, vol. 18, no. 6, p. 3026, Dec. 2020. DOI: 10.12928/telkomnika.v18i6.16174.

[5] F. Gelana and A. Yadav, "Firearm detection from surveillance cameras using image processing and machine learning techniques," in Tiwari, S., Trivedi, M., Mishra, K., Misra, A., Kumar, K. (eds) Smart Innovations in Communication and Computational Sciences. Advances in Intelligent Systems and Computing, vol 851. Springer, Singapore, 2019.

[6] P. Nandi, S. J. Hutchinson, and M. Fernando, "Multi object concealed threat detection by late time response analysis," 2016 16th Mediterranean Microwave Symposium (MMS), Abu Dhabi, United Arab Emirates, pp. 1-4, 2016. DOI: 10.1109/MMS.2016.7803848.

[7] A. R. Al-Qubaa and G. Y. Tian, "Automatic threat object classification based on extracted features from electromagnetic imaging system," 2012 IEEE International Conference on Imaging Systems and Techniques Proceedings, Manchester, UK, , pp. 164-169, 2012. DOI: 10.1109/IST.2012.6295536.

[8] G. Flitton, T.P. Breckon, and N. Megherbi, "A comparison of 3D interest point descriptors with application to airport baggage object detection in complex C.T. imagery. Pattern Recognit. Volume 46, Issue 9, pp. 2420-2436, 2013. DOI: 10.1016/j.patcog.2013.02.008.

[9] S. Li, S. Wang, Q. An, G. Zhao, and H. Sun, "Cylindrical mimo array-based near-field microwave imaging," IEEE Trans. Antennas Propag. 69(1), 612– 617, 2020. DOI: 10.1109/TAP.2020.3001438.

[10] Y. O. Yildiz, D. Q. Abraham, K. Panetta, and S. Agaian, ”A new concept of airport security screening,” in Proc. IEEE Conf. Technol. Homeland Secur., pp. 444–448, May 2008. DOI: 10.1109/THS.2008.4534493

[11] M. L. Janer and M. D. Rossetti, ”Simulation modeling of alternatives to avoid interruptions of the X-ray screening operation at security checkpoints,” in Proc. Winter Simulation Conf. (WSC), pp. 3005–3016, Dec. 2016. DOI: 10.1109/WSC.2016.7822335.

[12] J. Detlefsen, A. Dallinger, and S. Schelkshorn, ”Approaches to millimeter-wave imaging of humans”, European Radar Conference, pp. 279-282, 2004.

[13] Z. Wang, T. Chang and H. -L. Cui, ”Review of active millimeter wave imaging techniques for personnel security screening,” in IEEE Access, vol. 7, pp. 148336-148350, 2019. DOI: 10.1109/ACCESS.2019.2946736

[14] S. S. Ahmed, A. Schiessl, F. Gumbmann, M. Tiebout, S. Methfessel and L. -P. Schmidt, ”Advanced microwave imaging,” in IEEE Microwave Magazine, vol. 13, no. 6, pp. 26-43, Sept.-Oct. 2012. DOI: 10.1109/MMM.2012.2205772

[15] R. Appleby and R. N. Anderton, ”Millimeter-wave and submillimeter-wave imaging for security and surveillance,” in Proceedings of the IEEE, vol. 95, no. 8, pp. 1683-1690, Aug. 2007. DOI:10.1109/JPROC.2007.898832

[16] K. Mizuno et al., ”Millimeter-wave imaging technologies and their applications,” 2007 IEEE International Vacuum Electronics Conference, 15-17 May 2007. DOI: 10.1109/IVELEC.2007.4283195.

[17] H. Feng, Q. Shaoping , L. Hao, L. Yu, and W. Pengfei, ”Active imaging through dense fog by utilizing the joint polarization defogging and denoising optimization based on range-gated detection,” Opt. Express 31, 25527-25544, 2023. DOI: 10.1364/OE.491831.

[18] M. Peichl, E. Schreiber and M. Jirousek, ”Passive and active imaging using a novel radiometric imaging technique,” EUSAR 2012; 9th European Conference on Synthetic Aperture Radar, Nuremberg, Germany, pp. 182-185, 2012.

[19] Y. Meng, A. Qing, C. Lin, et al, ”Passive millimeter wave imaging system based on helical scanning. Sci Rep 8, 7852, 2018. DOI: /10.1038/s41598-018-25637-9.

[20] M. Kowalski, M. Kastek, M. Walczakowski, N. Palka, and M. Szustakowski, ”Passive imaging of concealed objects in terahertz and long-wavelength infrared,” Appl. Opt., vol. 54, no. 13, pp. 3826–3833, May 2015.

[21] C. Guo, F. Hu, and Y. Hu, ”Concealed object detection for passive millimeter-wave security imaging based on task-aligned detection transformer,” in IEEE Transactions on Instrumentation and Measurement, vol. 72, pp. 1-13, Art no. 5011513, 2023. DOI: 10.1109/TIM.2023.3261932.

[22] D. M. Sheen, D. L. McMakin, and T. E. Hall, “Three-dimensional millimeter-wave imaging for concealed weapon detection,” IEEE Trans. Microwave Theory Techn., vol. 49, no. 9, pp. 1581–1592, Sep. 2001, DOI: 10.1109/22.942570.

[23] A. Dallinger, S. Bertl and J. Detlefsen, ”Coherent millimeter-wave imaging for security applications,” 2007 European Radar Conference, pp. 28-31, 2007. DOI: 10.1109/EURAD.2007.4404928.

[24] S. Majumder, S. Gupta, and S. Dubey, ”Compressive sensing based active imaging system using programable coded mask and a photodiode,” in IEEE Photonics Journal, vol. 15, no. 3, pp. 1-7, Art no. 7800807, June 2023. DOI: 10.1109/JPHOT.2023.3273579.

[25] S. Seyedehzahra , A-B. Mehdi, and H. Shiva, ”Improving the quality of active millimeter wave standoff imaging by incorporating the cross-polarized scattering wave,” Opt. Express 29, 32603-32614, 2021.

[26] I. Ocket, D. Schreurs, V. Tavakol, F. Qi, B. Nauwelaers, and J. Stiens, ”Design challenges for millimeter wave active imaging systems,” The 7th European Radar Conference, Paris, France, pp. 312-315, 2010.

[27] Naruto Yonemoto, A. Kohmura, S. Futatsumori, K. Morioka and Y. Makita, ”Passive radio imaging of hybrid radar system for security inspections,” 2020 17th European Radar Conference (EuRAD), Utrecht, Netherlands, 2021. DOI: 10.1109/EuRAD48048.2021.00103.

[28] A. Setiawan, A. Yamawaki, N. Yonemoto, H. Nohmi, and H. Murata, ”Millimeter-Wave Imaging Using Dielectric Lens for Security Application,” 2022 19th European Radar Conference (EuRAD), Milan, Italy, Sep. 2022. DOI: 10.23919/EuRAD54643.2022.9924662.

[29] A. Setiawan, N. Yonemoto, H. Nohmi, and H. Murata, ”Analysis of millimeter-wave imaging using dielectric lens for fourier transformation,” 2022 Asia-Pacific Microwave Conference (APMC), Yokohama, Japan, Nov. 2022. DOI: 10.23919/APMC55665.2022.9999795

[30] Iizuka K, Lenses. In: Engineering optics, Springer Series in Optical Sciences, vol 35, 3rd edn, Springer, New York, 2008.

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