BaSrTiO$_3$ ceramic-polymer composite material lens antennas at 220–330 GHz telecommunication applications

S. Myllymäki, M. Teirikangas and M. Kokkonen✉

Ceramic ($Ba_{0.55}Sr_{0.45}Ti_{1.01}O_3$) – polypropylene polymer ER182 composites-based materials were applied for sub-THz range antenna lens application in telecommunications. Typical plano-convex -shaped lenses were simulated and measured with a standard rectangular waveguide at 220–330 GHz frequency band and applied on 150 mm on-air distance. The lens fabricated with ER182 polymer material increased the signal strength by 15 dB, ER182/7 vol% BST by 6 dB and ER182/30 vol% BST by −23 dB. Material loss tangent values were 0.008 for ER182, 0.034 for ER182/7%BST and 0.081 for ER182/30% BST. The directivity of ER182 material lens and WR3 waveguide combination was 26 dBi at 300 GHz.

Introduction: Current 5G telecommunication systems are climbing up to mm-wave frequencies and questions about 6G telecommunications systems are concerning beyond 100 GHz frequencies where one alternative frequency band is at 300 GHz in particular discussed by people in World Radio Congress (WRC) and International Telecommunication Union (ITU).

Optical [1] and electrical [2] principles are alternatives for processing signal modulation in sub-THz radio devices. However, both principles need either large antenna arrays [3] or lens antenna [4] structures on the air interface. Most of the presented lens antennas are build conventional high resistivity silicon [2, 4] or pure polymer materials [5–13] where typically lens material shapes, small details or macroscopic porosity are controlled by various fabrication methods. In addition, alumina material fabricated lens is presented in [14].

As antenna lenses the refractive index of the lens material is essential design parameter since it effects on the lens ability to shape the beam that radiates from the antenna. The feature of controlled dielectric value is not widely utilised so far. For example, Luneburg and Fresnel type of lenses need adjustable permittivity materials and either additive or moulding fabrication techniques for manufacturing case specific lenses. Antenna lens structures are case specific ie optimised design is based on antennas ability to illuminate the beam towards the lens and the lens has certain focal distance among other parameters. In order to improve amount of available tools for antenna lens design process the ceramic polymer composites are proposed in this paper. Certain composite materials are evaluated for 300 GHz band telecommunication systems and in particular hemispherical lens antennas. New composite materials can also be used instead of silicon or silicon dioxide based lens materials in the utilisation of additive fabrication technologies.

Experimental: The composite materials were fabricated with a mixing extrusion processing using modified polypropylene (ER182, NOF Co, Japan) as matrix material and $Ba_{0.55}Sr_{0.45}Ti_{1.01}O_3$ (BST, Praxair, USA) ceramic in paraelectric state as filler. ER182 (polypropylene–graft–poly(styrene–stat–divenylbenzene) with longer polymer chains were selected due to the extremely low dielectric losses (0.0002) at GHz region. The BST was selected as filler due to its high relative permittivity with moderately low losses at high frequencies.

The dielectric properties of the fabricated material samples were measured with TeraView TPS Spectra 3000 THZ spectroscopy equipment. The measured dielectric properties within frequency range from 01. to 1 THz are presented in Fig. 1. The measured properties at 300 GHz for composite materials are collected in Table 1.

Compositions with 7 and 29 vol.% of filler loading were chosen into the lens fabrication. The lenses were fabricated with a hot-pressing method with P O WEBER PW 20 HS Hotpress.

Fabricated hemispherical -shaped BST polymer composite lenses are presented in Fig. 2*a* in the order of ER182 polymer, ER182/7 vol% BST and ER182/30 vol% BST lenses from left to right all 30 mm of diameter. Lens measurement setup in Fig. 2*b* was constructed with two 220–330 frequency band extenders and WG3 (EIA standard) open-end waveguides located on 150 mm distance to each others. Short distance was selected to reduce potential signal reflections from the environment but enabling radiative near-field related behaviour affects the systems. Thus for replacing the measurements it is recommended to use the same distances. In addition, 150 mm distance was possible to simulate with 3D electromagnetic domain to assure the operation principle. Fabricated lenses were attached on aluminium lens holder at 12 mm focal distance, simulated and optimised earlier with CST Studio Suite. In such close proximity, the metal lens holder has negligible effects on the system. The transmitting waveguide is on the left side and the receiving waveguide on the right side of the view in Fig. 2*b*. Over-the-air transmission scattering parameters were measured by Keysight PNAX network analyser.

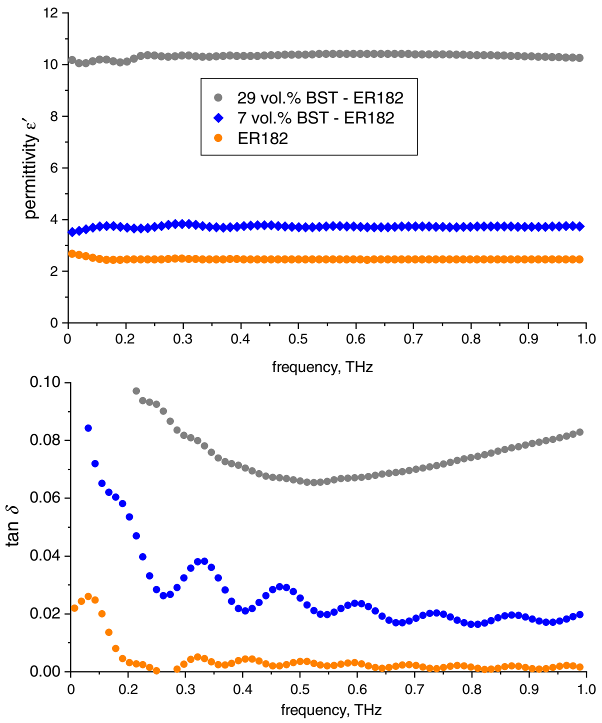

Fig. 1 *Measured dielectric properties of the used composite materials within frequency range of 0.1 to 1 THz*

Table 1: Measured dielectric properties of used composites at 300 GHz.

	εr	tan δ
ER182	2.47	0.008
7 vol. % BST -ER182	3.82	0.034
29 vol.% BST- ER182	10.34	0.081

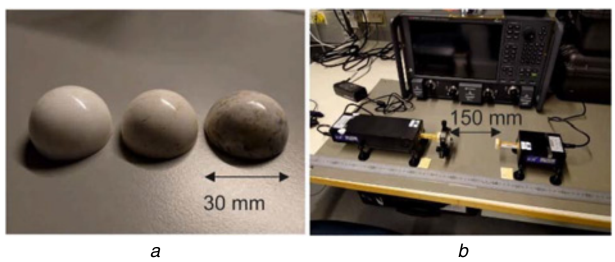

Fig. 2 *Fabricated ceramic-composite lenses and 300 GHz measurement system for waveguide lens feed*

a Lens fabricated with ER182, ER182/7%BST and ER182/30%BST materials
b Sub-THz measurement system consisting of Keysight PNAX and 220–330 GHz band frequency extenders installed at 150 mm distance, and the lens holder was at 12 mm distance to the transmitting waveguide

Measured signal transmission spectrum from WG3+lens to WG3 system is presented in Fig. 3. The transmitted signal was measured with three materials and without the lens for a reference. Waveguide extenders were levelled and aligned to each other's to provide straight line and maximum transmission power from the input to output waveguide. The empty space produced −50 dB transmitted signal power without remarkable signs of multipath transmission except the 8 dB notch at 260 GHz not existed with lens amplified signals. The repeatability of measurements were verified by removing the lens and replacing it on the same position proving as low as 0.3 dB signal variation over the band. The same size of repeatability was measured for extender movements.

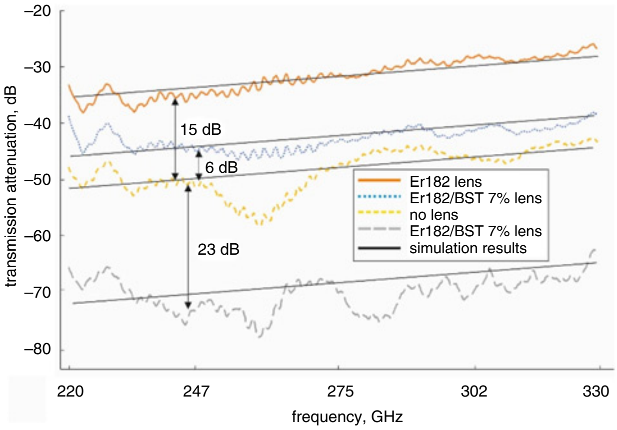

Fig. 3 *Measured and simulated signal attenuation results at 150 mm waveguide distance with varied lens configurations, no lens, ER182, ER182/7% BST and ER182/30%BST material lenses*

ER182 polymer lens was adjusted on 12 mm of the distance from the waveguide as providing the maximum signal strength in the system. ER182 lens improved the signal strength by 15 dB all over the measured band 220–330 GHz. In this particular measurement case, the signal strength was −35 dB at 220 GHz increasing to −27 dB at 330 GHz. ER182/7%BST composite lens was adjusted on 5 mm distance from the waveguide improving the signal level by 6 dB in the lower band 220–275 GHz and 4 dB in the upper band 275–330 GHz. ER182/30% BST composite lens was adjusted on 4 mm distance from the waveguide and decreasing the signal strength by 23 dB. Signal power decrements were caused due to the high loss tangent and signal absorption to the material. Over-the-air measurement system was simulated and measured parameters were compared to simulated ones.

In the measurements, the focal distance of ER182 lens was varied and the signal transmission spectrum was measured (Fig. 4). When focal length was increased from 12 to 15 mm the slope of the signal strength over the band was increased. The signal strength in the lower band was decreased and higher band increased. The sensitivity of focal length to signal coupling is 2 dB / mm at low band and 1 dB / mm at high band in this particular measurement setup.

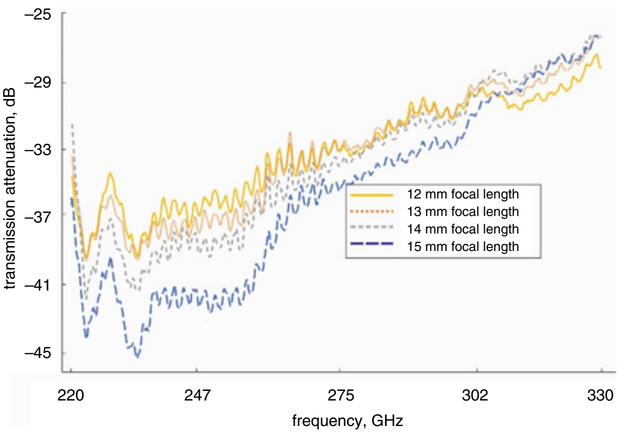

Fig. 4 *Measured signal attenuation at 150 mm waveguide distance with varied focal distance of 12, 13, 14 and 15 mm*

The radiation patterns of WG3 waveguide and polymer composite lenses were measured by vertically moving the receiving unit and the results are presented in Fig. 5. The waveguide lens system directivity was 25 dBi on 250 GHz, 26 dBi at 300 GHz and 27 dBi at 330 GHz and the half-power beam width (HPBW) was 9 degrees. The results were verified by simulations meaning that the value of 26 dBi directivity is correlated with measured 15 dB amplification in the system. BST composite materials especially between 0–7 vol% can be utilised for telecommunication applications for example Luneburg and Fresnel lens structures and they can be applied for modern fabrication methods such as 3D printing and structural electronics.

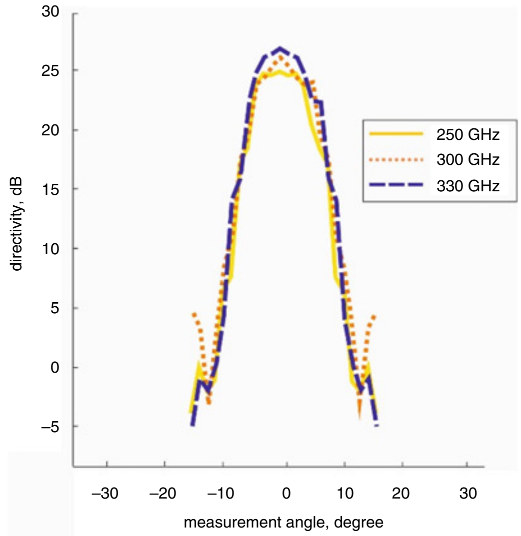

Fig. 5 *Measured radiation patterns and directivity results at 250, 300 and 330 GHz*

Conclusion: Ceramic (Ba 0.55Sr0.45Ti1.01O3) polypropylene polymer ER182 composites based materials were applied for sub-THz range antenna lens application. Plano-convex lenses were simulated and measured with waveguides at 220–330 GHz frequency and 150 mm distance. The ER182 polymer lens increased the signal strength by 15 dB, ER182/7 vol% BST increased the signal by 6 dB and ER182/30 vol% BST decreased the signal by 23 dB. Material loss tangent values were 0.008 for ER182, 0.034 for ER182/7%BST and 0.081 for ER182/30%BST. The directivity of ER182 lens WR3 waveguide systems was 26 dBi at 300 GHz.

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References

1 Lacombe, E., Belem-Goncalves, C., Luxey, C., *et al.*: '300 GHz OOK transmitter integrated in advanced silicon photonics technology and achieving 20 Gb/s.' 2018 IEEE Radio Freq. Integr. Circuits Symp. (RFIC), Philadelphia, PA, 2018, pp. 356–359. doi: 10.1109/RFIC.2018.8428983

2 Song, H., Hamada, H., and Yaita, M.: 'Prototype of KIOSK data downloading system at 300 GHz: design, technical feasibility, and results', *IEEE Commun. Mag.*, 2018, **56**, (6), pp. 130–136, doi: 10.1109/MCOM.2018.1000939

3 Akyildiz, I., and Jornet, J.: 'Realizing ultra-massive MIMO (1024 × 1024) communication in the (0.06–10) terahertz band', *Nano. Commun. Netw.*, 2016, **8**, pp. 46–54, doi.org/10.1016/j.nancom.2016.02.001

4 Chudpooti, N., Duangrit, N., Akkaraekthalin, P., *et al.*: '220–320 GHz hemispherical Lens antennas using digital light processed photopolymers', *IEEE Access*, 2019, **7**, pp. 12283–12290, 10.1109/ACCESS.2019.2893230

5 Alazemi, A.J., Yang, H.H., and Rebeiz, G.M.: 'Double bow-tie slot antennas for wideband millimeter-wave and terahertz applications', *IEEE Trans. Terahertz Sci. Technol.*, 2016, **6**, (5), pp. 682–689

6 Nguyen, T.K., and Tran, H.H.: 'Air gap effect on antenna characteristics of slitline and stripline dipoles on an extended hemispherical lens substrate', *Appl. Comput. Electromagn. Soc. J.*, 2018, **33**, (9), pp. 1018–1025

7 Vangerow, C.V., Goettel, B., Ng, H.J., *et al*.: 'Circuit building blocks for efficient in-antenna power combining at 240 GHz with non-50 Ohm amplifier matching impedance'. Digital Paper - IEEE Radio Frequency Integrated Circuits Symp., Honolulu, USA, 2017, pp. 320–323
8 Sauleau, R., Fernandes, C.A., and Costa, J.R.: 'Review of lens antenna design and technologies for mm-wave shaped-beam applications'. ANTEM 2005–11th Int. Symp. Antenna Technology Applied Electromagnetics Conf. Proc., St.Malo, France, 2005, pp. 1–5
9 Lacombe, E., Gianesello, F., Gulan, H., *et al*.: 'Low-cost 3D-printed 240 GHz plastic lens fed by integrated antenna in organic substrate targeting sub-THz high data rate wireless links'. 2017 IEEE Antennas Propagation Society Int. Symp. Proc., Janua, 2017, vol. 2017, pp. 5–6
10 Sun, J., and Hu, F.: 'Three-dimensional printing technologies for terahertz applications: a review', *Int. J. RF Microw. Comput. Eng.*, 2020, **30**, (1), pp. 1–17
11 Pan, W., and Zeng, W.: 'Far-field characteristics of the square grooved-dielectric lens antenna for the terahertz band', *Appl. Opt.*, 2016, **55**, (26), pp. 7330–7336. [Online]. Available at: http://ao.osa.org/abstract.cfm?URI=ao-55-26-7330
12 Konstantinidis, K., Feresidis, A.P., Constantinou, C.C., *et al*.: 'Low-THz dielectric Lens antenna with integrated waveguide feed', *IEEE Trans. Terahertz Sci. Technol.*, 2017, **7**, (5), pp. 572–581
13 Wu, G.B., Zeng, Y.S., Chan, K.F., *et al*.: 'Highgain circularly polarized lens antenna for terahertz applications', *IEEE Antennas Wirel. Propag. Lett.*, 2019, **18**, (5), pp. 921–925
14 Zhang, M., Clochiatti, S., Rennings, A., *et al*.: 'Antenna design for sub-harmonic injection-locked triple barrier RTD oscillator in the 300 GHz band'. 2019 Second Int. Workshop on Mobile Terahertz Systems (IWMTS), Bad Neuenahr, Germany, 2019, pp. 1–4. doi: 10.1109/IWMTS.2019.8823656