Aalto University

OPEN ACCESS

This is an electronic reprint of the original article.
This reprint may differ from the original in pagination and typographic detail.

Karki, Sabin; Ala-Laurinaho, Juha; Karttunen, Aki; Viikari, Ville

Integrated Lens Antennas for E-band

Published in:
Proceedings of the 48th European Microwave Conference

DOI:
10.23919/EuMC.2018.8541385

Published: 01/01/2018

Document Version
Peer-reviewed accepted author manuscript, also known as Final accepted manuscript or Post-print

Please cite the original version:
Karki, S., Ala-Laurinaho, J., Karttunen, A., & Viikari, V. (2018). Integrated Lens Antennas for E-band. In *Proceedings of the 48th European Microwave Conference* (pp. 1151-1154). IEEE. https://doi.org/10.23919/EuMC.2018.8541385

This material is protected by copyright and other intellectual property rights, and duplication or sale of all or part of any of the repository collections is not permitted, except that material may be duplicated by you for your research use or educational purposes in electronic or print form. You must obtain permission for any other use. Electronic or print copies may not be offered, whether for sale or otherwise to anyone who is not an authorised user.

Integrated Lens Antennas for E-band

Sabin Kumar Karki#1, Juha Ala-Laurinaho#2, Aki Karttunen#3 Ville Viikari#4
#Dept. of Electronics and Nanoengineering, Aalto University, Finland
[1]sabin.karki@aalto.fi, [2]juha.ala-laurinaho@aalto.fi, [3]aki.karttunen@aalto.fi, [4]ville.viikari@aalto.fi

***Abstract*— This work evaluates the performance of two ILA with different dielectric materials. Two elliptical ILAs of 32 mm radius are designed using Rexolite (ϵ_r= 2.53 and tanδ = 0.0013) and PREPERM® L450 (ϵ_r = 5.01 and tanδ = 0.0046) materials. The gain and beam-steering properties of these ILAs were thoroughly investigated using raytracing simulations and measurements at E-band. Despite the higher loss tangent, the ILA with L450 material gives 29.3 dBi gain compared to 28.7 dBi of Rexolite material at 73 GHz. The measured gain scan loss for steering angle of the 24° beam is 4.3 dB and 4.9 dB for the Preperm-ILA and Rexolite-ILA, respectively. Additionally, the work focuses on the dielectric property characterization of the L450 material at millimeter wave frequencies.**

***Keywords*— millimeter waves, integrated lens antenna, dielectric properties.**

I. Introduction

The next generation of cellular communication system, 5G, is moving towards millimeter-wave frequencies. Although, specific frequencies have not been allocated yet, the potential candidates include 26-30 GHz, 37-42 GHz and E-band i.e., 71-76/81-86 GHz [1], [2]. Millimeter-wave frequencies have high propagation and antenna losses and therefore high gain antennas are desired. Additionally, the antennas are desired to be compact for practical implementation.

Although bulky in size, an integrated lens antenna (ILA) with beam-focusing and steering ability has been a popular choice in the field of telecommunication, radar and imaging [3], [4], [5]. The size and shape of an ILA is dependent on the gain requirement and dielectric properties of the material used. In [6], permittivity between 3 - 5 is recommended for optimum gain performance. With higher permittivity, the ILA becomes more compact and the spillover loss reduces. However, the higher permittivity materials in comparison to low permittivity materials have the higher loss tangent. This feature causes an increases in dielectric loss for high permittivity materials. In practice, materials with low permittivity i.e., 2-3, and lower loss tangent are used in an ILA design which accounts for the bulkiness of the ILA [6], [7], [8].

Therefore, this study investigates the possibility of using the relatively high permittivity materials like PREPERM® L450 in the ILA design. Additionally, the dielectric properties of L450 material is characterized at E-band. Then, the Preperm-ILA and Rexolite-ILA with the same diameter are designed and simulated. The simulated and measured gain performance of the Preperm-ILA is compared with the traditional Rexolite-ILA to evaluate its feasibility.

The paper is organized as follows. In Section 2, an ILA characteristics is studied and the dielectric properties of the L450 material is estimated. The designs of the two ILAs and their simulation results are presented in Section 3. Section 4 presents the measurement results and its analysis. Finally, Section 5 presents conclusions.

II. ILA characteristics and L450 characterization

The basic properties of an ILA are well described in [9] and [10]. Furthermore, the design guidelines of an ILA have been presented in [11]. Based on these guidelines, the height and losses variation of a 120-mm ILA with varying permittivity (constant tanδ = 0.0006) is studied, as shown in Fig. 1. For the given tanδ, the dielectric and reflection losses increase marginally with respect to permittivity. The material permittivity is inversely proportional to the height of an ILA. With increasing permittivity, the height of an ILA decreases and consequently the spillover loss decreases. Beyond permittivity 5, the decrease in spillover loss is minimal and is neutralized by the increase in the reflection loss and dielectric loss. Hence, the overall loss saturates, and consequently, the gain saturates. Although the tanδ increases with permittivity, in this simulation study tanδ is constant.

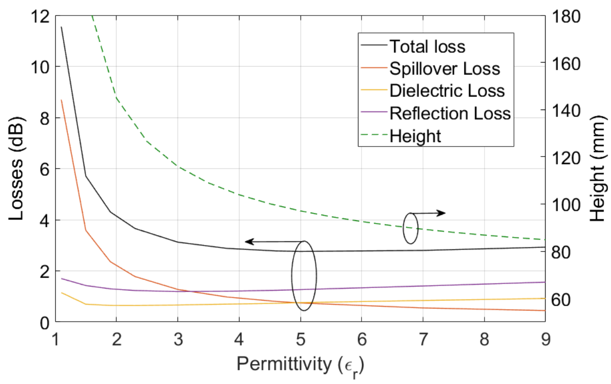


Fig. 1. Variation of losses and height of the 120-mm ILA with loss tangent tanδ = 0.0006.

Based on the above results, the L450 material was selected for the ILA design. During the initial ILA design and simulation, the dielectric properties ϵ_r = 4.5 and tanδ = 0.0046 are used, as provided by the manufacturer [12]. The simulated directivity and gain variation of the Preperm-ILA with respect to the diameter is shown in Fig. 2. The result shows that the directivity of an ILA is proportional to its diameter. However, the gain starts to decrease for the larger ILA dimension due to higher dielectric loss.

A free-space method is used for the dielectric property measurement of the L450 material at 73.5 GHz. Rectangular

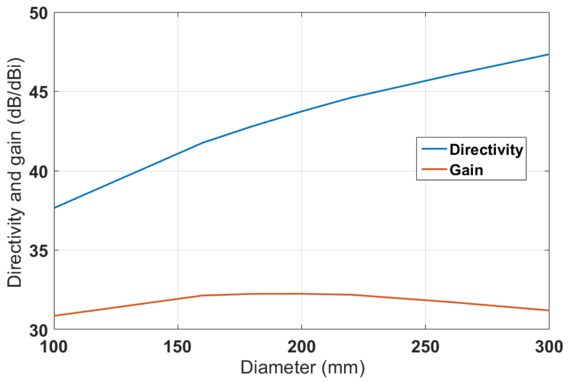


Fig. 2. Simulated gain and directivity variation of the Preperm-ILA w.r.t. diameter.

material samples of cross section 100 $\times$ 50 mm^2 and varying thickness (i.e., 5, 10, 20, 30, and 50 mm) are placed between horn antennas that are connected to a vector network analyser (VNA). The VNA measures the transmission coefficient S21 of each sample in frequency domain. The frequency domain transmission coefficient is transformed to the time-domain as shown in Fig. 3. The time-domain signals are gated to minimize the reflections and other effects of the surroundings. Delay of time-domain signals arrival with respect to varying material thickness is used to calculate the permittivity [13]. The permittivity was found to be 5.01 at 73.5 GHz. Loss tangent calculation using the free-space measurement did not provide accurate results, with tanδ varying between 0.001-0.009. These measured results were in close range of 0.0046, the value provided by the manufacturer [12]. Therefore, the value is used during the design and simulations.

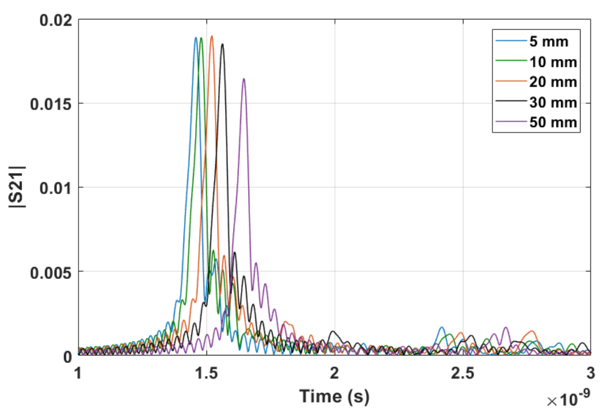


Fig. 3. Time-domain response of the L450 material samples with varying thickness at 224 mm antenna separation distance.

III. ILAs and Simulation Results

An in-house ray-tracing program is used to design elliptical ILAs with Rexolite and L450 materials. In case of the Rexolite material, the dielectric properties, ϵ_r = 2.53 and tanδ= 0.0013, are used [14]. The simulated radiation pattern of the WR-10 open-ended waveguide is used as the feed source in the ray-tracing program. The 2D-cuts of the designed rotationally symmetric ILAs are shown in the Fig. 4. Both these ILAs are designed with 32 mm radius R and the minor axis of the ellipse is $1.1 \times R$. The larger minor axis of the collimating surface helps to minimize the reflections in the lens-air interface and minimizes the scanloss [11]. In the ray-tracing simulation only the rays exiting from the collimating elliptical section is considered for the far-field calculation. In practice, absorbers and PVC support structures are placed along the extension section of the ILA. The extension length of both lenses are grooved in such a way that most of the fields hitting this section exits to absorber and reflections from the extension surface remain minimum. Differences in the grooves of two ILAs is expected to have no effect on the performace.

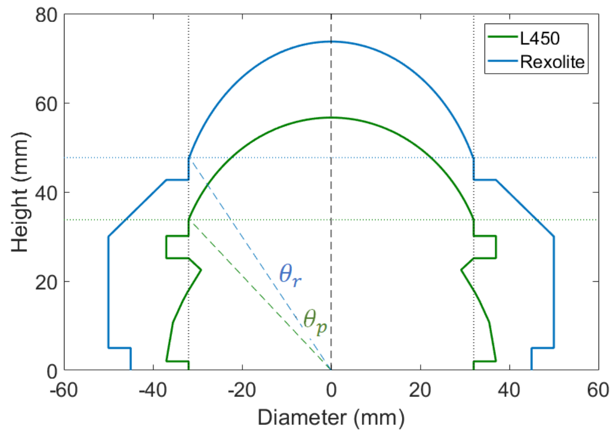


Fig. 4. 2D-cut view of the designed ILAs with Preperm and Rexolite materials.

Comparison between the Rexolite-ILA and the Preperm-ILA dimesnions and simulation performances are shown in Table 1 and Fig. 5. As the diameter of both the ILAs is the same, the directivity is also comparable. However, the total loss of the Preperm-ILA is 0.7 dB higher compared to rexolite ILA. As discussed in introduction section, the spillover loss and dielectric loss are the major contributors in the Rexolite-ILA and Preperm-ILA, respectively. The simulation results show that the boresight gain of Rexolite-ILA is 1 dB higher compared to that of the Preperm-ILA. The feed source is moved with step interval 1.65 mm and 3.1 mm for the Preperm-ILA and Rexolite-ILA, respectively, to achieve $-$ 3-dB beam-overlapping in the far-field radiation pattern. For 24° beamsteering angle, the Preperm-ILA have 5.7 dB scanloss compared to 4.6 dB of rexolite ILA.

IV. Measurement Results

The designed ILAs are fabricated with milling process and the prototypes are shown in Fig. 6 (a). The measurements are done in the planar near-field scanner from 67 GHz to 115 GHz at the frequency interval of 3 GHz. WR-10 waveguide is used as the feed antenna. The scanning plane of 191 $\times$ 191 mm^2, scan interval of 1.25 mm, and scanning velocity of 32 mm/s is used for the measurements. Near-field measurement of the reference horn antenna with known gain is used to calculate the gain of the ILAs.

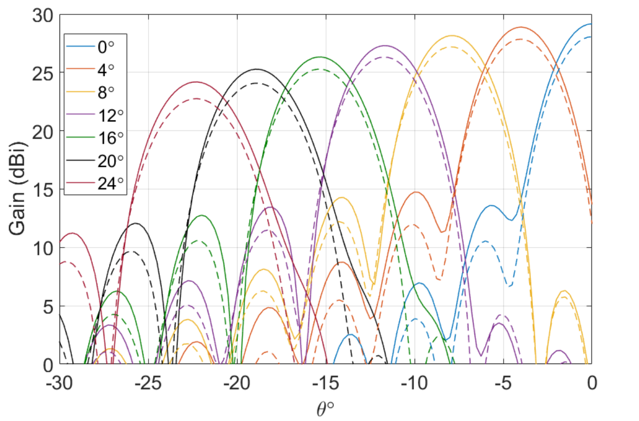


Fig. 5. Simulation results of the Rexolite-ILA(—) and Preperm-ILA(- -) at different beamsteering angles.

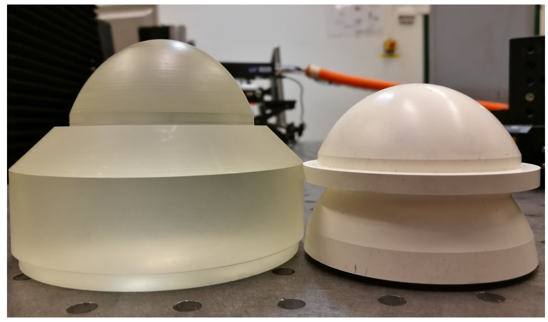
Table 1. Relevant dimensions and simulation values of the designed lenses at 73 GHz.

Parameters	**Rexolite lens** ($\epsilon_r = 2.53$)	**L450 lens** ($\epsilon_r = 5.01$)
Total height (mm)	72.72	56.67
Extension length (mm)	47.7	33.76
Total loss	4.68	5.33
Reflection loss (dB)	1.05	0.81
Spillover loss(dB)	2.72	0.98
Dielectric loss(dB)	0.9	3.74
Directivity (dB)	33.8	33.53
Gain (dBi)	29.12	28.06

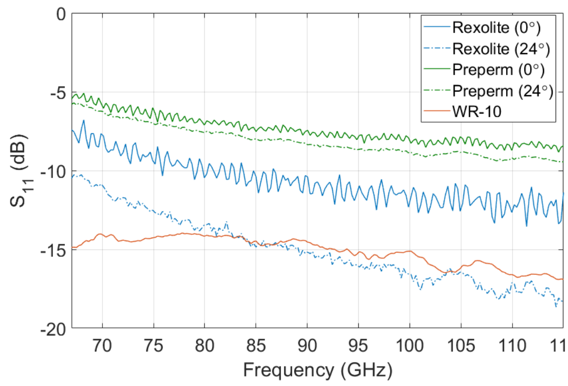
The S-parameter response of WR-10 waveguide feeding both ILAs at different feed position is shown in Fig. 6 (b). For both ILAs, the reflection coefficient S_{11} decreases as the feed moves away from the focal point. Variation in the S_{11} is mainly contributed by the reflections from the collimating surface. As feed moves away from the focal point, these reflected rays from the collimating surface are directed away from the feed, thereby reducing the S_{11}.

The measured realized gain of both ILAs at different beamsteering angles are shown in Fig. 7 (a). At 73 GHz, the measured realized gain of the Rexolite-ILA, i.e. 28.03 dBi is 1 dB lower in comparison to its simulation result. In case of the Preperm-ILA realized gain, i.e., 28.3 dBi is 0.25 dB higher compared to its simulated gain. The realized gain takes reflection loss in consideration. However, such reflection losses can be minimized with the feed specifically designed for the ILA. The calculated gain from the measured realized gain and reflection coefficient is shown in Fig. 7 (b). At 73 GHz, the boresight gain of the Preperm-ILA is 29.35 dBi compared to 28.71 dBi of Rexolite-ILA. Measurement results shows that the gain of the Preperm-ILA is 0.65 dB higher than the Rexolite-ILA. Based on the measurement results, it is reasonable to conclude that loss tangent of the L450 material is slightly lower than 0.0046 at 73 GHz.

Fig. 8 (a) and (b) presents the realized gain with respect to beam direction at 73 GHz and the boresight realized gain with respect to frequency of both ILAs. For 24° beamsteering angle, the realized gain scanloss of the Preperm-ILA and

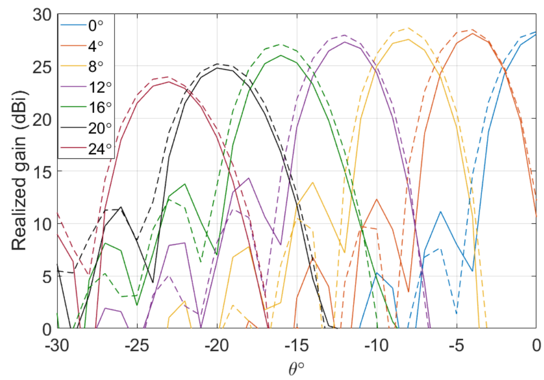


(a)

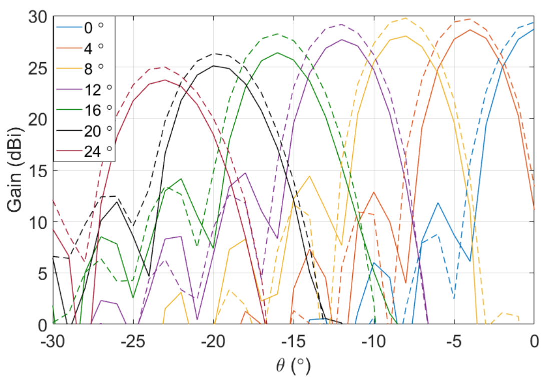


(b)

Fig. 6. (a) Fabricated prototypes and (b) S-parameter response of the WR-10 waveguide feeding both ILAs at different positions.



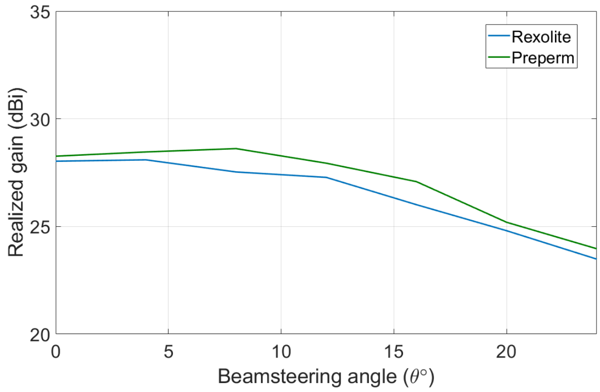
(a)



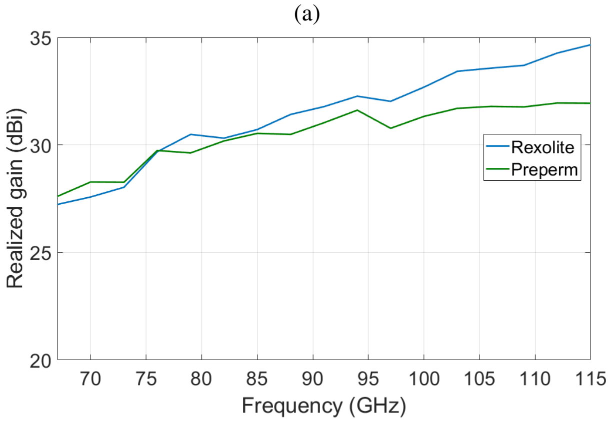
(b)

Fig. 7. (a) Realized gain and (b) gain comparison of the Preperm-ILA (- -) and Rexolite-ILA (—) at 73 GHz.

Rexolite-ILA is 4.3 dB and 4.9 dB, respectively. At lower frequencies, i.e. E-band, the gain performance of both lens is comparable to each other. However, at higher frequencies, i.e. above 90 GHz, the Rexolite-ILA has better gain. The directivity of WR-10 waveguide fed to the Preperm-ILA is higher compared to the Rexolite-ILA due to larger effective aperture. Also, the feed directivity increases with frequency. For the Preperm-ILA, the feed becomes highly directive that causes the under-illumination of the collimating surface. Additionally, as the $\theta_p > \theta_r$, see Fig. 4, the Preperm-ILA requires wider beam feed to avoid under-illumination of collimating surface. Therefore, as the operating frequency and ILA material varies, it is necessary to change the feed, accordingly. The decrease of the gain may also contributed by the increase in dielectric loss with respect to frequency.



(a)



(b)

Fig. 8. Realized gain performances of the Rexolite-ILA and Preperm-ILA w.r.t. (a) beamsteering angle at 73 GHz and (b) frequency for the boresight beams.

V. Conclusion

In this work, the feasibility of using relatively high permittivity material in ILA design is studied. Simulation results helped to conclude that, it is not feasible to use lossy materials to design very large ILAs. The maximum dimension and achievable gain of an ILA is dependent on material loss tangent. Simulation and measurement study between the Preperm-ILA and Rexolite-ILA of 32 mm radius gave comparable results in E-band. Additionally, the Preperm-ILA is smaller in dimension which makes it more feasible for practical use.

Acknowledgment

We would like to thank Business Finland for supporting the work through 5WAVE project. We would also like to thank Mr. Eino Kahra and Premix Group for supporting the ILA fabrication.

References

[1] T. S. Rappaport, S. Sun, R. Mayzus, H. Zhao, Y. Azar, K. Wang, G. N. Wong, J. K. Schulz, M. Samimi, and F. Gutierrez, “Millimeter wave mobile communications for 5G cellular: It will work!” *IEEE Access*, vol. 1, pp. 335–349, 2013.

[2] C. Dehos, J. L. Gonzlez, A. D. Domenico, D. Ktnas, and L. Dussopt, “Millimeter-wave access and backhauling: the solution to the exponential data traffic increase in 5G mobile communications systems?” *IEEE Communications Magazine*, vol. 52, no. 9, pp. 88–95, September 2014.

[3] J. Ala-Laurinaho, J. Aurinsalo, A. Karttunen, M. Kaunisto, A. Lamminen, J. Nurmiharju, A. V. Räisänen, J. Säily, and P. Wainio, “2-D beam-steerable integrated lens antenna system for 5G E -band access and backhaul,” *IEEE Transactions on Microwave Theory and Techniques*, vol. 64, no. 7, pp. 2244–2255, July 2016.

[4] A. Mozharovskiy, A. Artemenko, A. Sevastyanov, V. Ssorin, and R. Maslennikov, “Beam-steerable integrated lens antenna with waveguide feeding system for 71-76/81-86 GHz point-to-point applications,” in *2016 10th European Conference on Antennas and Propagation (EuCAP)*, April 2016, pp. 1–5.

[5] J. R. Costa and C. A. Fernandes, “Integrated imaging lens antenna with broadband feeds,” in *The Second European Conference on Antennas and Propagation, EuCAP 2007*, Nov 2007, pp. 1–6.

[6] S. K. Karki, J. Ala-Laurinaho, V. Viikari, and R. Valkonen, “Lens antenna design for e-band point-to-point radio links,” in *2017 Progress In Electromagnetics Research Symposium - Spring (PIERS)*, May 2017, pp. 1625–1631.

[7] A. Karttunen, J. Säily, A. Lamminen, J. Ala-Laurinaho, R. Sauleau, and A. V. Räisänen, “Using optimized eccentricity rexolite lens for electrical beam steering with integrated aperture coupled patch array,” *Progress In Electromagnetics Research B*, vol. 44, pp. 345–365, 2012.

[8] A. Karttunen, J. Ala-Laurinaho, R. Sauleau, and A. V. Räisänen, “Extended hemispherical integrated lens antenna with feeds on a spherical surface,” in *2013 7th European Conference on Antennas and Propagation (EuCAP)*, April 2013, pp. 2539–2543.

[9] D. F. Filipovic, S. S. Gearhart, and G. M. Rebeiz, “Double-slot antennas on extended hemispherical and elliptical silicon dielectric lenses,” *IEEE Transactions on Microwave Theory and Techniques*, vol. 41, no. 10, pp. 1738–1749, Oct 1993.

[10] M. J. M. van der Vorst, P. J. I. de Maagt, and M. H. A. J. Herben, “Scan-optimized integrated lens antennas,” in *1997 27th European Microwave Conference*, vol. 1, Jerusalem, Isarel, Sept 1997, pp. 605–610.

[11] A. Karttunen, J. Ala-Laurinaho, R. Sauleau, and A. V. Räisänen, “Reduction of internal reflections in integrated lens antennas for beam-steering,” *Progress in Electromagnetics Research*, vol. 134, pp. 63–78, 2013.

[12] Premix Oy. (2018) Low-loss thermoplastics with tunable dielectric constant. [Online]. Available: https://www.preperm.com/products/raw-materials

[13] B. Will and I. Rolfes, “Comparative study of moisture measurements by time domain transmissometry,” in *2013 IEEE SENSORS*, Nov 2013, pp. 1–4.

[14] J. W. Lamb, “Miscellaneous data on materials for millimetre and submillimetre optics,” *International Journal of Infrared and Millimeter Waves*, vol. 17, no. 12, pp. 1997–2034, 1996.