Monostatic Reflectivity Measurement of Radar Absorbing Materials at 310 GHz

Anne Lönnqvist, Aleksi Tamminen, Juha Mallat, and Antti V. Räisänen, *Fellow, IEEE*

***Abstract*—This paper presents monostatic reflectivity measurements of radar absorbing materials at 310 GHz in a phase-hologram-based compact range. The radar cross-section method was used and the backscattered reflection was measured with horizontal and vertical polarizations in plane-wave conditions. Transmission was also studied. The reflectivity was measured over an incidence angle of 0°–45°. The reflectivity of Thomas Keating Terahertz RAM at normal incidence was found to be −56 dB—the smallest of the studied materials. The reflectivity of carpet material measured was also below −40 dB and it was found to be suitable for use as an absorber. The results are in line with those available from previous studies of reflectivity and complement them with new materials, frequency, and angle information.**

***Index Terms*—Compact range, monostatic reflectivity, radar absorbing materials, radar cross-section (RCS) method.**

I. INTRODUCTION

RADAR absorbing materials are needed to suppress unwanted reflections, e.g., in compact test ranges and to minimize radar cross section (RCS) of a target. Absorbers can also be used as beam dumps in quasi-optical systems and as calibration loads in radiometers [1], [2]. Application-specific absorbing materials have been designed for these different purposes. Attenuation can be caused by electric or magnetic losses and by the structure of the absorber.

In this paper, attention is concentrated on absorbers, which can be used when building a compact antenna or RCS measurement range for submillimeter wavelengths. Characteristics of absorbing materials need to be known when building a compact range. With proper placement of absorbers, the amount of absorbers needed can be minimized and low reflectivity level of the background can be assured. Possible standing waves can also be suppressed. For this purpose, we have characterized four commercially available radar absorbing materials and three carpets. The use of carpets as absorbers at submillimeter wavelengths is appealing due to their low price compared to the commercially available absorbing materials.

In most of the absorbers used in anechoic chambers, carbon-impregnated polyurethane foam is used to provide loss. The absorbers are usually shaped so that the geometrical transformation from the free space to lossy medium provides a dielectric gradient and reduces reflections. Pyramidal and wedge-shaped painted absorbers are commonly used. A layer of low reflection paint is used to provide protection and to reduce the amount of carbon dust in the measurement range. These kinds of absorbers scatter more energy to the directions satisfying the grating equation, as shown with measurements in [3] for pyramidal and wedge-shaped absorbers below 18 GHz and in [4] for a wedge-shaped Far-Infrared Radiation Absorbing Material (FIRAM) at 584 GHz. However, usually electromagnetic simulations cannot exactly predict the scattering behavior of absorbers and, therefore, it needs to be verified with measurements before designing their placement in a compact range.

Earlier, bistatic, and specular measurements of the absorbers investigated here have been carried out at MilliLab, Helsinki University of Technology, Espoo, Finland [5], [6]. However, these measurements were done in near field conditions. Now the campaign is completed with monostatic compact range measurements, where the absorber sample is placed into a plane-wave region and measured over an angle range of 45° from the normal of the absorber. The transmission of the absorbers is also measured. In [1] and [2], the reflectivity has been measured only in the direction of the normal of the absorber, but for compact antenna test range (CATR) design, more information on the characteristics of the absorber are needed.

In the RCS method [7] used here, the absorber sample is fastened on a heavy metal backing plate, the plate is installed on a rotating fixture, and the RCS pattern of the ensemble is recorded. The perfect reflection from the backside of the plate can be used as a reference and the characteristics of the absorber can be evaluated by comparing the reflection from the absorber to the reference. Since the result is obtained by comparing these two reflections, the absolute amplitude of the RCS pattern does not need to be calibrated. The measurement range itself will be presented in more detail in Section II. In Section III, details of the absorber materials and the measurement are described. The results, discussion, and conclusion are presented in Sections IV–VI, respectively.

II. COMPACT RCS MEASUREMENT RANGE

The measurement range used for absorber characterization has originally been designed for measuring RCS of scaled models [8]. In a compact range, we are able to evaluate the absorber samples in more realistic conditions than with near-field measurements. The plane-wave region needed for RCS evaluation is created with a phase hologram [9], which transforms

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The authors are with MilliLab, Radio Laboratory, The Smart and Novel Radios Research Unit, Helsinki University of Technology, Espoo FI-02015 TKK, Finland (e-mail: anne.lonnqvist@tkk.fi).

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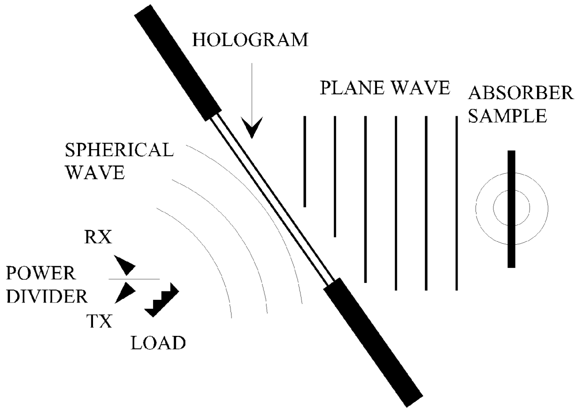

Fig. 1. Hologram-based test range. (RX = receiver, TX = transmitter).

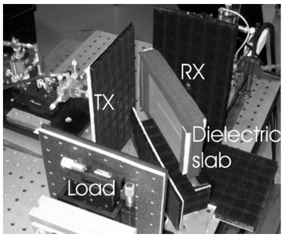

Fig. 2. Closer view of the radar setup.

the spherical wave radiated by the feed into a plane wave. As a diffractive element, the phase hologram is narrowband so when wanting to cover a wide range, several holograms need to be designed and manufactured. The region where the scaled model, or here, a sample of an absorber, is placed is what is called the quiet zone (QZ). The setup is shown in Fig. 1. The distance from the receiver/transmitter to the hologram and also from the hologram to the target is 1 m.

The phase hologram is realized as a groove structure on a thin Teflon plate. In this case, the phase-hologram operation is optimized for operation at 310 GHz, which is suitable for our compact ranges. The changing depth of the grooves causes the phase modulation of the transmitted field. The hologram structure of size 28 cm × 24 cm was fabricated on a 5-mm-thick Teflon plate. The amplitude and phase variations of the QZ field are approximately 2 dB and 10° peak-to-peak, respectively. The diameter of the QZ is 12 cm. Outside the QZ, the amplitude of the field drops quickly, approximately 10 dB when moving from a distance of 6 cm (= QZ diameter) to 8 cm from the axis of the QZ.

The instrumentation is based on a millimeter-wave vector network analyzer (AB Millimètre MVNA-8–350) with submillimeter-wave extensions. Corrugated horns are used as transmitting and receiving antennas. A dielectric slab with 3-dB power division is used as a directional coupler. The load absorber, which is made of Thomas Keating Terahertz (TK THz) RAM, is placed on a translation stage to enable its proper placement. TK THz RAM is also used around the transmitter and receiver, as can be seen in Fig. 2. Additional absorbers were placed around the setup before measurements to reduce reflections.

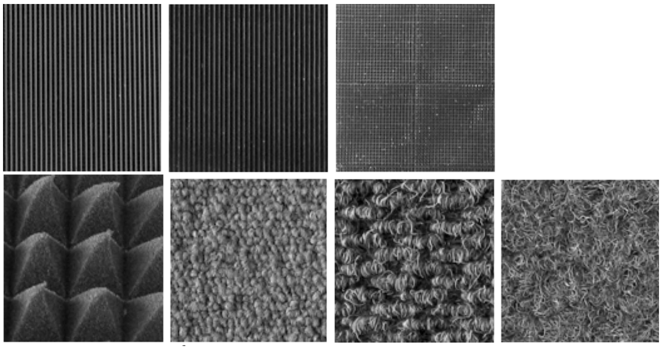

Fig. 3. 5 × 5 cm^2 samples of FIRAM, TERASORB, TK THz RAM, Eccosorb, carpet #1, carpet #2, and carpet #3. The size of the samples measured was 10 × 10 cm^2.

III. ABSORBERS AND MEASUREMENT SYSTEM

Seven different materials presented in Fig. 3 were selected for investigation: FIRAM-500 and TERASORB-500 by the Submillimeter-Wave Technology Laboratory, University of Massachusetts at Lowell; Space-qualified Tessalating Terahertz RAM by Thomas Keating Ltd., Billingshurst, West Sussex, U.K., unpainted Eccosorb VFX-NRL-2 by Emerson and Cuming Microwave, Company, Westerlo, Belgium, and three carpets, referred to here as carpets #1–#3. These were also studied [6] with bistatic and specular near-field measurements. The sample sizes were 10 × 10 cm^2.

FIRAM-500 is a wedge-type iron loaded silicone absorber designed for submillimeter wavelengths; it is available as sheets of size 61 × 61 cm^2. TERASORB-500 has the same wedge-type structure, but it is made of carbon loaded ethylene vinyl acetate. The size of the interlocking tiles is 10 × 10 cm^2. Both materials have a groove opening angle of 22.5°, groove spacing of 1.55 mm, groove depth of 3.8 mm, and thickness of 7.6 mm. TK THz RAM is made of carbon loaded polypropylene plastic. It consists of small pyramids of 1.5-mm height and 1-mm spacing. The size of the interlocking tiles is 2.5 × 2.5 cm^2 and the thickness is 7.5 mm. It has been designed for frequencies of 100–1000 GHz.

The unpainted Eccosorb VFX-NRL-2 for millimeter wavelengths is a pyramidal carbon loaded polyurethane foam absorber, which consists of pyramids with a height of 38 mm and a spacing of 19 mm. The thickness of the material is 58 mm. Unpainted material was selected since it had been previously noted that the paint itself could increase the reflection when the absorber was used at 310 GHz.

Carpet #1 consists of woven knots with a separation of approximately 2 mm. The pile fiber is 100% polyamide. The knots are bound to an intermediate layer, which is glued to a felt-like base layer. The double calendared vinyl coating is stabilized with glass fiber reinforcement. The thickness of the material is 5.5 mm. Carpet #2 has knots woven made of polypropylene fiber, which are glued onto a synthetic rubber backing. The thickness of the carpet is 9 mm. The carpet #3 is made of polypropylene fibers, which are held together with glue and a rubber backing. The thickness of the material is 8 mm.

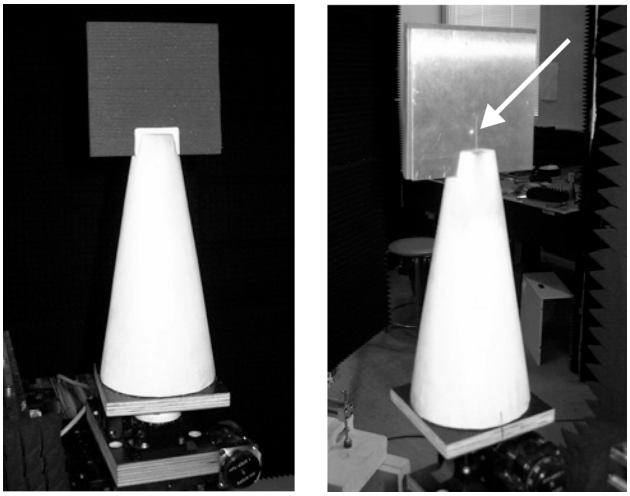

Fig. 4. Sample of FIRAM-500 placed on a sample holder. Front and back views. On the metal plate, the laser beam also used to assure accurate alignment of the sample can be seen (indicated with an arrow).

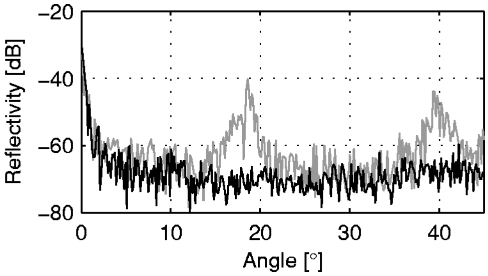

Fig. 5. Reflection pattern of FIRAM-500 at horizontal polarization at 310 GHz. Grey line = wedges vertically, black line = wedges horizontally.

The sample of the absorber was placed on a sample holder (see Fig. 4). The support is a column made of extruded polystyrene foam (Styrofoam). The dielectric constant of Styrofoam was measured and found to be 1.048 at 310 GHz. Thus, the reflections from the support column are so low that with current measurement setup, it is not possible to separate them from the background reflection. We have been able to measure RCS down to −42 decibels relative to a squre meter (dBsm) for the vertical polarization and −36 dBsm for the horizontal polarization [8].

The support column itself was placed on a rotation/translation stage, which enables rotation of the target and also movement of the target in the z-direction. The reflection from the absorber is separated from the background reflection by moving the target in the z-direction and, as a result, a periodic response is obtained. The field component caused by the moving absorber can be evaluated from the variation of the amplitude and the phase [8].

An aluminum plate was placed behind the absorber sample. A laser beam was used to assure proper alignment of the plate and absorber. The beam was pointed to the aluminum plate from a distance of 1.2 m and the position of the plate was tuned until the transmitted and reflected beams converged. It was calculated that the angular alignment precision was better than 0.12°.

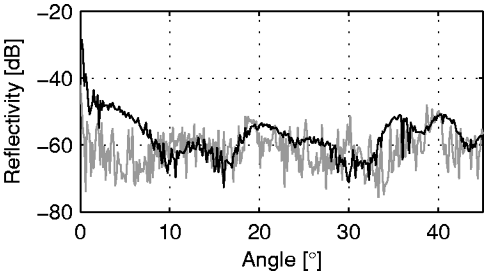

Fig. 6. Reflection pattern of TERASORB-500 at horizontal polarization at 310 GHz. Grey line = wedges vertically, black line = wedges horizontally.

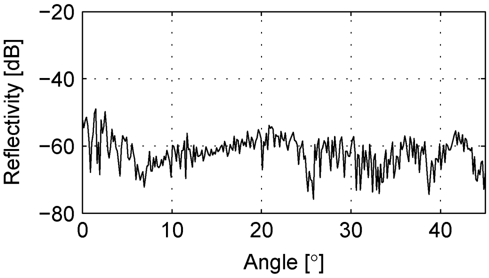

Fig. 7. Reflection pattern of TK THz RAM at horizontal polarization at 310 GHz.

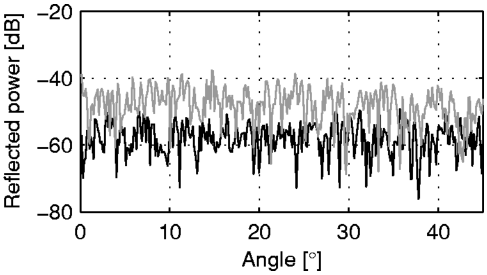

Fig. 8. Reflection pattern of Eccosorb VFX-NRL-2 and carpet #1 (grey line) at horizontal polarization at 310 GHz.

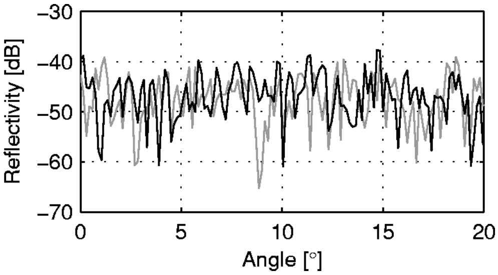

Fig. 9. Reflection patterns of two different samples of carpet #1.

The transmission of the absorbers at 310 GHz was measured during QZ testing. The measured amplitude of the QZ field with an absorber (without the metal back plate) placed in front of the field probe was compared to the amplitude without the absorber. The measured amplitude was averaged over 120 samples taken in a period of 1 min.

IV. MEASUREMENT RESULTS

The reflectivity of the absorber samples was measured over an incidence angle of 0°–45°. The measurements were done both at horizontal and vertical polarization at 310 GHz. The wedge-type absorbers were measured in two positions, i.e.,

TABLE I
MAXIMA AND MINIMA OF REFLECTIVITES OF THE INVESTIGATED MATERIALS AT 310 GHz

	Reflectivity, Max. [dB], H-pol.	V-pol.	Reflectivity, Min. [dB], H-pol.	V-pol.	Transmission [dB] V-pol.
FIRAM-500					-24
Wedges horizontal	-30	-26	<-70	-60	
Wedges vertical	-31	-30	-70	-66	
TERASORB-500					-33
Wedges horizontal	-29	-41	-70	-52	
Wedges vertical	-41	-30	<-70	-65	
TK THz RAM	-51	-56	-70	-70	-50
Eccosorb	-50	-55	-70	-70	-50
VFX-NRL-2					
Carpet #1	-40	-40	-60	-60	-17
Carpet #2	-40	-40	-60	-60	-25
Carpet #3	-21	-20	-60	-55	-5

wedges horizontally and wedges vertically. Measured patterns for FIRAM, TERASORB, TK THz RAM, Eccosorb, and carpet #1 are shown in Figs. 5–9. The maxima and minima of the reflectivity and transmission of all the materials investigated are gathered in Table I. We were able to measure the reflectivity down to −70 dB compared to the reflection from the reference.

When the wedges of FIRAM are vertical, i.e., against the polarization, the absorber forms a reflection grid according to Bragg's equation (1)

$$2d\sin\theta = n\lambda \tag{1}$$

where d is the distance between wedges (i.e., parallel slits), θ is the angle of the maxima, n is an integer, and λ is the wavelength. Peaks predicted by (1) can be seen around angles 18° (−40 dB) and 39° (−45 dB) (see Fig. 5).

Between these maxima, the reflectivity level is below −60 dB. The level of reflectivity in the direction of the normal of the absorber is −31 dB. When the wedges are horizontal, the reflectivity is below −60 dB, except in the direction of the normal of the absorber it is a maximum of −30 dB. The transmission is quite high, i.e., −24 dB.

TERASORB has a fingerlike pattern at both positions (see Fig. 6). The performance is clearly better near the normal of the absorber when the wedges are vertical, i.e., against the polarization, i.e., −41 dB versus −29 dB when the wedges are horizontal. The peaks caused by the grid structure can be seen, but their level is a lot lower than for FIRAM, approximately −50 dB. The transmission is also lower, i.e., −33 dB.

The fingerlike structure of the reflection pattern caused by the pyramidal structure of TK RAM can be seen in Fig. 7. The level of reflectivity in the direction of the normal of the absorber is −51 dB and below −50 dB in the other directions. The transmission is low, below −50 dB.

The same kind of fingerlike pattern was not seen when measuring Eccosorb (see Fig. 8). At submillimeter wavelengths, the pyramids of Eccosorb are very large compared to wavelength, therefore the diffraction peaks are so close to each other that they cannot be seen in Fig. 8. As the absorber is made of foam material, its structure is also not as uniform as, for example, the structure of TK RAM. The reflectivity of Eccosorb is low, below −50 dB for all angles, and the transmission is also below −50 dB. Overall performance of the Eccosorb absorber is adequate for use at submillimeter wavelengths.

The monostatic reflectivity level of carpet #1 is about the same to all directions (see Figs. 8 and 9), i.e., it scatters energy to all directions. The reflectivity is surprisingly low, below −40 dB. The transmission of carpet #1 is higher than that for commercial absorbers, i.e., −17 dB. The levels of reflectivity of different samples of the same material are alike, as can be seen in Fig. 9. The samples are from different manufacturing batches and also the color of the samples is different. The reflection pattern of carpet #2 is very similar. It does have one advantage, the transmission is lower, approximately −25 dB. Carpet #3 has the worst performance with the reflection in the direction of the normal of the carpet being −20 dB, which can partly be due to its high transmission, measured to be −5 dB, so the metal plate can partly be seen through the carpet. To the other directions, the performance is about the same as for the other carpets, i.e., scatters to all directions.

V. DISCUSSION

In these monostatic measurements, TK THz RAM performed best among the materials investigated. Clearly it works better to certain reflection angles and with proper placement of the absorbers, reflectivity level better than −60 dB can be expected. In [2], the reflection in the direction of the normal has been measured to be −48 dB at 406 GHz, and in [1], −42 dB at 576 GHz and −35 dB at 672 GHz, thus the result obtained here; −51−−56 dB at 310 GHz is very well in line with the previous measurements. In [1] and [2], there was no information on reflectivity to other angles than in the direction of the normal of the absorber.

Eccosorb VFX-NRL-2 also performed very well. It seems to scatter energy to all directions just like the carpet materials investigated. In [6], the material was investigated without the pyramids, i.e., the flat side of the absorber was measured, so the results cannot be compared. Also, as stated in [3], if the pyramids are large compared to wavelength, even though absorber tips tend to scatter coherently, the absorber walls built of several absorber panels scatter incoherently and the reflectivity level of a wall is considerably lower than that of a single panel, or as here, part of one panel.

From the carpet materials, the best choice would be carpet #2 due to its high attenuation in transmission measurements and low overall reflectivity level. This carpet had the best performance among the carpets also in bistatic measurements. The material is inexpensive compared to the commercial absorber materials (by the order of tens of times). Since the need of absorbing material in a large-sized compact range can be over 500 m^2, this type of difference reduces the costs significantly. The reflectivity is still higher than for the best materials so the placement of the carpets has to be designed carefully when using them together with better absorber materials.

The performance of TERASORB and FIRAM is strongly polarization dependent. For both, the performance is good when excluding the peaks caused by the wedge-type structure. With this kind of material, even more attention has to be paid to proper placement since even a small mistake in placement can cause a 20-dB difference. These absorbers did not perform as good as expected. However, this can be due to their design, which was optimized to frequencies higher than 500 GHz. For FIRAM, the reflection in the direction of the normal was approximately -30 dB at 310 GHz and, in [4], it was measured to be approximately -38 dB at 584 GHz. TERASORB and FIRAM are at their best when used with one polarization only. In compact ranges, this very seldom is the situation.

The reflection coming back to the transmitter was not measured in [6] so it is not possible to do a direct comparison of the results, but the order of superiority is the same as in [6] with the exception of Eccosorb, which was measured without the pyramids in the previous study. In the far-field situation, the maximum measured reflectivity is clearly lower than what was measured with near-field measurements. In the monostatic measurements reported here, it was possible to eliminate the effect of background reflections better than those reported in [6] and, furthermore, direct coupling was not a problem in the measurements reported here. For compact ranges, absorber measurements done in plane-wave conditions can be estimated to resemble a real-life situation better than results of measurements done in the near field of the absorber.

The test samples were relatively small and they filled the QZ almost entirely. Even though the metal plate was totally covered with the absorber, diffraction from the edges could have caused some uncertainty to the measurement result though any clear indication of this kind of phenomena was not found. Getting larger samples of the materials to the tests or a smaller QZ diameter would eliminate the possibility of this kind of effect showing in the measurement results.

In the future, also making bistatic measurements in far-field conditions would be of interest. With a phase hologram setup containing two holograms on a moving axis, this would be possible. This kind of measurement would give a better understanding of the scattering behavior of the absorber. The cross-polarization performance of absorbers should also be tested. Low reflectivity may be due to energy transforming from one polarization to another.

In this study, we have tested absorbers at only one frequency, namely, at 310 GHz. This is due to the narrowband behavior of our hologram-based RCS measurement setup. However, we believe that the results obtained are useful, and also demonstrate how a relatively simple measurement setup can be used to test absorbers in far-field conditions at submillimeter wavelengths.

VI. CONCLUSION

Monostatic reflectivity of a set of absorbing materials was investigated at 310 GHz at an angle range from the normal of the absorber to 45°. As expected, TK THz RAM manufactured by Thomas Keating Ltd. was found to have the best performance. Eccosorb VFX-NRL-2 also performed well, better than -50-dB attenuation to all angles. This is better than expected for an absorber that is designed for the millimeter-wave region. The Eccosorb material investigated here was unpainted so carbon dust can cause trouble in some applications. Since its pyramids are large compared to wavelength and absorber walls scatter incoherently, it can be expected to perform even better when a large absorber wall is built.

A floor carpet had the next best performance, over -40-dB attenuation to all angles. This can be found adequate at least for the noncritical places in the compact range. A combination of all of these three, i.e., TK THz RAM, Eccosorb, and carpets, is a good compromise. Use of the carpets considerably brings down the costs of building a measurement range.

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Anne Lönnqvist was born in Somero, Finland, in 1977. She received the Master of Science (Tech.) (with honors) and Licentiate of Science (Tech.) degrees in electrical engineering from the Helsinki University of Technology (TKK), Espoo, Finland, in 2001 and 2004, respectively, and is currently working toward the Doctor of Science (Tech.) degree at TKK.

Since 2000, she has been a Research Assistant and Research Engineer with the Radio Laboratory, TKK. Her current research interests include millimeter-wave measurement techniques with a focus on hologram applications.

Aleksi Tamminen was born in Ruotsinpyhtää, Finland, in 1982. He received the Bachelor's (Tech.) degree in electrical engineering from the Helsinki University of Technology (TKK), Espoo, Finland, in 2005 , and is currently working toward the Master of Science (Tech.) degree at TKK.

He is currently a Research Assistant involved with millimeter-wave measurement projects with the Radio Laboratory, TKK.

Juha Mallat was born in Lahti, Finland, in 1962. He received the Master of Science (Tech.) (with honors), Licentiate of Science (Tech.), and Doctor of Science (Tech.) degrees in electrical engineering from the Helsinki University of Technology (TKK), Espoo, Finland, in 1986, 1988, and 1995, respectively.

Since 1985, he has been with the Radio Laboratory (and its Millimeter Wave Group), TKK, as a Research Assistant, Senior Teaching Assistant, and Research Associate until 1994. From 1995 to 1996, he was a Project Manager and Coordinator involved with an education project between TKK and the Turku Institute of Technology. Since 1997, he has been a Senior Scientist with the Millimetre Wave Laboratory of Finland (MilliLab), European Space Agency (ESA) External Laboratory, Helsinki, TKK, with the exception of a period of one year from 2001 to 2002 when he served as a Professor (protem) of radio engineering with TKK. His research interests and experience cover various topics in radio-engineering applications and measurements, especially in millimeter-wave frequencies. He has also been involved in building and testing millimeter-wave receivers for space applications.

Antti V. Räisänen (S'76–M'81–SM'85–F'94) received the Master of Science (Tech.), Licentiate of Science (Tech.), and Doctor of Science (Tech.) degrees in electrical engineering from the Helsinki University of Technology (HUT), Espoo, Finland, in 1973, 1976, and 1981, respectively.

In 1989, he was appointed Professor Chair of Radio Engineering, HUT, after holding the same position as an Acting Professor in 1985 and 1987–1989. He has been a Visiting Scientist and Professor with the Five College Radio Astronomy Observatory (FCRAO), University of Massachusetts at Amherst (1978–1981), Chalmers University of Technology, Göteborg, Sweden (1983), Department of Physics, University of California at Berkeley (1984–1985), Jet Propulsion Laboratory, California Institute of Technology, Pasadena (1992–1993), and Paris Observatory and University of Paris 6 (2001–2002). He currently supervises research in millimeter-wave components, antennas, receivers, microwave measurements, etc. at the Radio Laboratory, HUT, and Millimetre Wave Laboratory of Finland (MilliLab—European Space Agency (ESA) External Laboratory). The Smart and Novel Radios Research Unit (SMARAD), HUT (which he leads), obtained in 2001 the national status of Center of Excellence in Research from The Academy of Finland after competition and international review. He has authored and coauthored over 400 scientific or technical papers and six books, most recently, *Radio Engineering for Wireless Communication and Sensor Applications* (Artech House, 2003). He also coauthored the chapter "Radio-Telescope Receivers" in *Radio Astronomy* (Cygnus-Quasar Books, 1986, 2nd ed.).

Dr. Räisänen was secretary general of the 12th European Microwave Conference in 1982. He was chairman of the IEEE Microwave Theory and Techniques (MTT)/Antennas and Propagation (AP) Chapter in Finland from 1987 to 1992. He was conference chairman for the 22nd European Microwave Conference in 1992, and for the "ESA Workshop on Millimeter Wave Technology and Applications" in 1998. From 1995 to 1997, he served on the Research Council for Natural Sciences and Engineering, Academy of Finland. From 1997 to 2000, he was vice-rector for research and international relations of HUT. From 2002 to 2005, he was an associate editor for the IEEE TRANSACTIONS ON MICROWAVE THEORY AND TECHNIQUES.