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TECHNICAL REPORT

colour inside

Transmitting and receiving equipment for radiocommunication – Radio-over-fibre technologies for electromagnetic-field measurement –
Part 3: Antenna near-field pattern measurement using optical techniques in terahertz-wave bands

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IEC TR 63099-3:2022-03(en)

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TRANSMITTING AND RECEIVING EQUIPMENT FOR RADIOCOMMUNICATION – RADIO-OVER-FIBRE TECHNOLOGIES FOR ELECTROMAGNETIC-FIELD MEASUREMENT –

Part 3: Antenna near-field pattern measurement using optical techniques in terahertz-wave bands

FOREWORD

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The text of this Technical Report is based on the following documents:

Draft	Report on voting
103/207/DTR	103/224/RVDTR

Full information on the voting for its approval can be found in the report on voting indicated in the above table.

The language used for the development of this Technical Report is English.

This document was drafted in accordance with ISO/IEC Directives, Part 2, and developed in accordance with ISO/IEC Directives, Part 1 and ISO/IEC Directives, IEC Supplement, available at www.iec.ch/members_experts/refdocs. The main document types developed by IEC are described in greater detail at www.iec.ch/publications.

A list of all parts in the IEC 63099 series, published under the general title *Transmitting and receiving equipment for radiocommunication – Radio-over-fibre technologies for electromagnetic-field measurement*, can be found on the IEC website.

Future documents in this series will carry the new general title as cited above. Titles of existing documents in this series will be updated at the time of the next edition.

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INTRODUCTION

This document provides technical information on the antenna near-field pattern measurement in terahertz-wave bands above 100 GHz, using optical techniques such as electro-optic (EO) frequency down-conversion. Two techniques are covered: a synchronous system based on a self-heterodyne technique, and an asynchronous system based on a phase noise-cancellation technique. The synchronous system is the vector network analyser (VNA) type system, which provides the RF signal to the antenna under test (AUT) and measures the amplitude and phase distributions of its radiation. In this system, the radio frequency (RF) and local oscillator (LO) signals are optically generated based on the self-heterodyne technique to realize the wide frequency tunability and precise phase measurements simultaneously. On the other hand, the asynchronous system applies to the AUT which integrates the transmitters where the measurement system cannot provide the RF signal to the AUT for the measurements. In this system, an optical frequency comb is used for the LO signal, and the electronics cancel residual frequency and phase noise between the RF and LO signals. Both systems employ the EO sensors for the field mapping which reduces the disturbance to the field compared with the waveguide-type probes employed in the conventional VNA-based measurement system.

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TRANSMITTING AND RECEIVING EQUIPMENT FOR RADIOCOMMUNICATION – RADIO-OVER-FIBRE TECHNOLOGIES FOR ELECTROMAGNETIC-FIELD MEASUREMENT –

Part 3: Antenna near-field pattern measurement using optical techniques in terahertz-wave bands

1 Scope

This part of IEC 63099 provides technical information about the methods for an antenna near-field measurement in the terahertz-wave band. The methods are applied to the frequency bands above 100 GHz, which has potential for use in terahertz wireless communication. The methods consist in measuring the amplitude and phase distributions of the electromagnetic field at the near-field range of on-chip antenna devices which integrate RF and IF components. This document also gives examples of the far-field pattern calculated from the measured near-field pattern.

2 Normative references

The following documents are referred to in the text in such a way that some or all of their content constitutes requirements of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

IEEE Std 145TM-2013, *IEEE Standard for Definitions of Terms for Antennas*

3 Terms, definitions and abbreviated terms

3.1 Terms and definitions

For the purposes of this document, the terms and definitions given in IEEE Std 145-2013 and the following apply.

ISO and IEC maintain terminological databases for use in standardization at the following addresses:

- IEC Electropedia: available at http://www.electropedia.org/
- ISO Online browsing platform: available at http://www.iso.org/obp

3.1.1
EO probe
probe in which an electro-optic (EO) crystal is attached to the optical fibre so that the electric field in the free-space can be measured by moving this probe

3.1.2
self-heterodyne technique
technique which enables the measurement of the phase information coherently using frequency fluctuating free-running lasers

3.1.3
uni-travelling-carrier photodiode
high-speed photodiode which can operate at terahertz-wave bands

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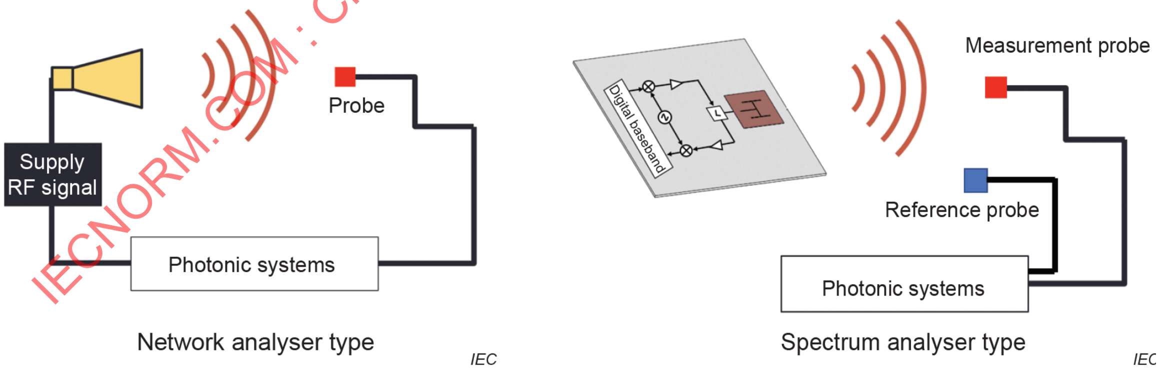
3.2 Abbreviated terms

EO	electro-optic
EM	electromagnetic
GRIN	graded index
HR	high-reflection
IF	intermediate frequency
LD	laser diode
LO	local oscillator
O/E	optical to electrical
OFC	optical frequency comb
PMF	polarization maintaining fibre
RF	radio frequency
SNR	signal-to-ratio
TIA	transimpedance amplifier
UTC-PD	uni-travelling-carrier photodiode
VNA	vector network analyser

4 Practical examples of antenna near-field measurement using optical techniques in terahertz-wave bands

4.1 Overview

This document introduces practical examples of antenna near-field measurement using optical techniques in terahertz-wave bands. Two systems are discussed: a synchronous system based on a self-heterodyne technique, and an asynchronous system based on a phase noise-cancelling technique (Figure 1 a) and Figure 1 b)). In both systems, electro-optic (EO) probes are used for the measurement. The terahertz signal will be down-converted to the low-frequency signal in both systems by a non-polarimetric EO frequency down-conversion technique.



a) Synchronous system b) Asynchronous system

Figure 1 – Proposed measurement system

The remainder of this document is organized as follows. Subclause 4.2 describes the principle of the non-polarimetric EO frequency down-conversion technique. In 4.3, the configuration of the synchronous measurement system based on a self-heterodyne technique is described, and examples of the near-field measurement are shown. In 4.4, the configuration of the asynchronous measurement system based on the phase noise-cancelling technique is described, and examples of the near-field measurement taken by this system are given. A

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comparison between the results obtained by the synchronous and asynchronous systems is drawn in 4.5.

4.2 Non-polarimetric EO frequency down-conversion technique

Figure 2 shows a typical configuration of the EO probe used in both systems. The sensor head consists of an EO crystal, high-reflection (HR) mirror, spacer, and graded-index (GRIN) lens. The sensor head is attached to the polarization-maintaining optical fibre (PMF) to make up the EO probe. The GRIN lens collimate the 1,55 µm probe beam (LO signal) emitted from the PMF. The polarization direction of the probe beam is aligned with the slow-axis of the PMF fibre and the principal dielectric axes of the EO crystal. The diameter of the collimated probe beam in the EO crystal is typically 0,1 mm to 0,2 mm, which limits the ultimate spatial resolution. The THz field (RF signal) to be measured interacts with the optical LO (probe beam) in the EO crystal. The probe beam is reflected by the HR mirror and is focused on the PMF by the GRIN lens.

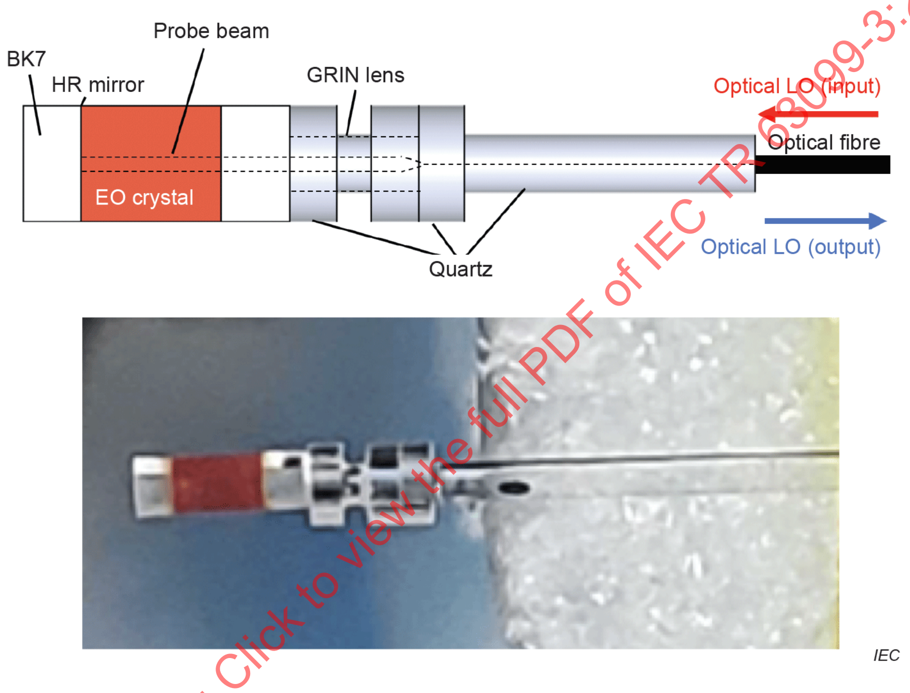

Figure 2 – Schematic diagram and photograph of EO probe

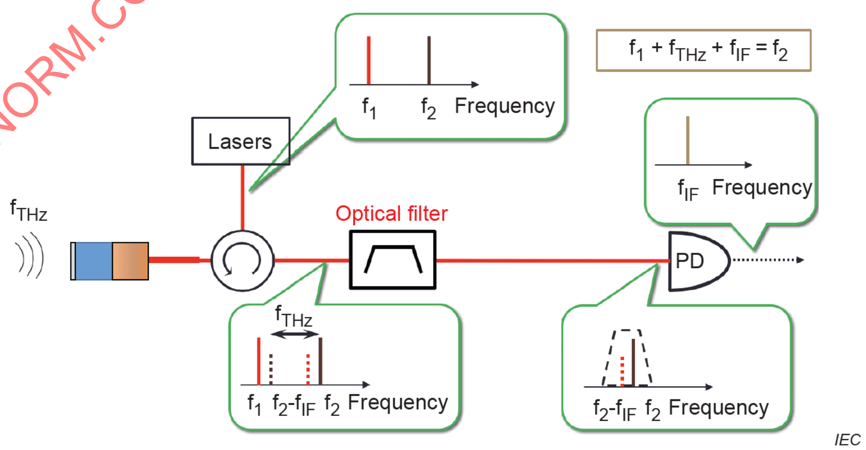

Figure 3 – Principle of the non-polarimetric EO frequency down-conversion technique

Figure 3 illustrates the principle of the non-polarimetric EO frequency down-conversion using frequency spectra. The detection principle is based on the coherent detection of the sideband generated by the electromagnetic (EM) field to be detected. In other words, the EM field is up-converted to the optical frequency region through the phase modulation of the LO beam in the

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EO crystal. Then, the generated sideband is down-converted to the intermediate frequency (IF) band by the coherent optical detection. The optical LO, which consists of two frequency components f_1 and f_2, interacts with the EM field, and sidebands are generated. The upper sideband of f_1 and the lower sideband of f_2 are shown in Figure 3. There are two carrier and sideband pairs to be considered as heterodyne candidates. The optical filter extracts a single pair and is then detected with the low-speed optical-to-electrical (O/E) converter, such as a photodiode (PD). The coherent detection of the weak sideband, which reflects the amplitude and the phase information of the EM wave to be detected, is achieved with a strong LO signal. The amplitude and the phase of the IF signal are simultaneously measured using a lock-in amplifier.

4.3 Synchronous system based on a self-heterodyne technique

4.3.1 General

The synchronous system is the vector network analyser (VNA) type system. The system generates the RF signal and LO signal to measure the amplitude and phase distribution of a near-field. The RF and LO signals can be generated using two free-running laser diodes (LDs). Although the frequency of the RF signal fluctuates, not only the amplitude but also the phase distribution is visualized due to the self-heterodyne technique.

4.3.2 Principle and system configuration

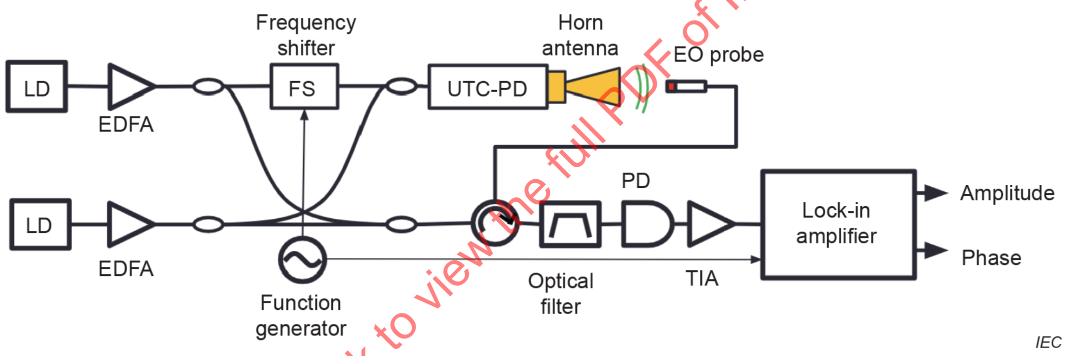

Figure 4 – Schematic diagram of the synchronous system based on the self-heterodyne technique

Figure 4 shows the system configuration of the synchronous measurement system based on the self-heterodyne technique. Two free-running 1,55 µm LDs are used as optical sources. The frequencies of the LDs are set as f_1 and f_2 ($f_2 > f_1$) and combined using PMF couplers to produce a beat note at a frequency of $f_{THz} = f_2 - f_1 - f_s$ for THz wave generation (RF). Here, an EO frequency shifter is used to shift the frequency of the LD1 (f_1) by f_s (typically 100 kHz to 10 MHz) for self-heterodyne detection. High-speed PD such as a uni-travelling-carrier photodiode (UTC-PD) can be used as an O/E converter. For the LO signal, a beat note is used as a probe beam for the non-polarimetric EO frequency down-conversion. The IF signal is amplified by the transimpedance amplifier (TIA) and supplied to the lock-in amplifier. The measured amplitude and phase data are acquired by a personal computer.

4.3.3 Example of near-field measurement

For the proof-of-concept experiment, the terahertz wave at 300 GHz band was generated with the UTC-PD and emitted from the conical horn antenna. In this experiment, a 4-N, N-dimethylamino-4'-N'- methyl-stilbazolium-tosylate (DAST) crystal was used as the EO crystal. The diameter of the probe beam in the EO crystal was approximately 0,1 mm.

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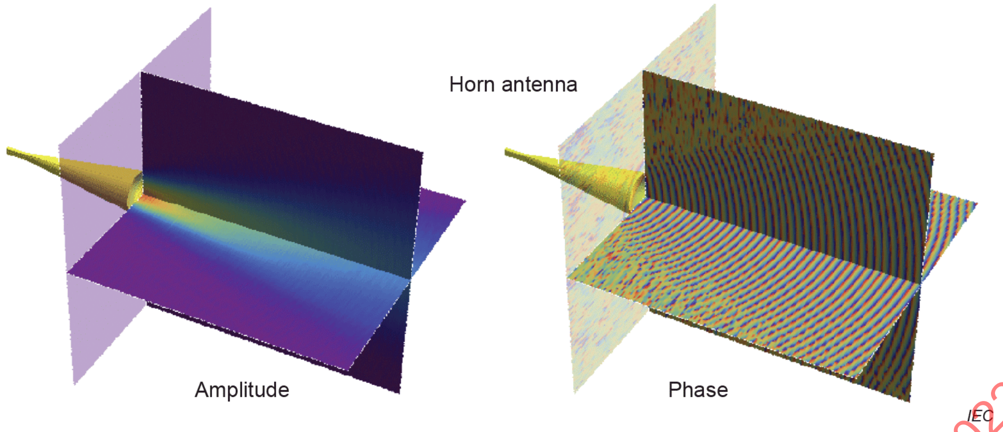
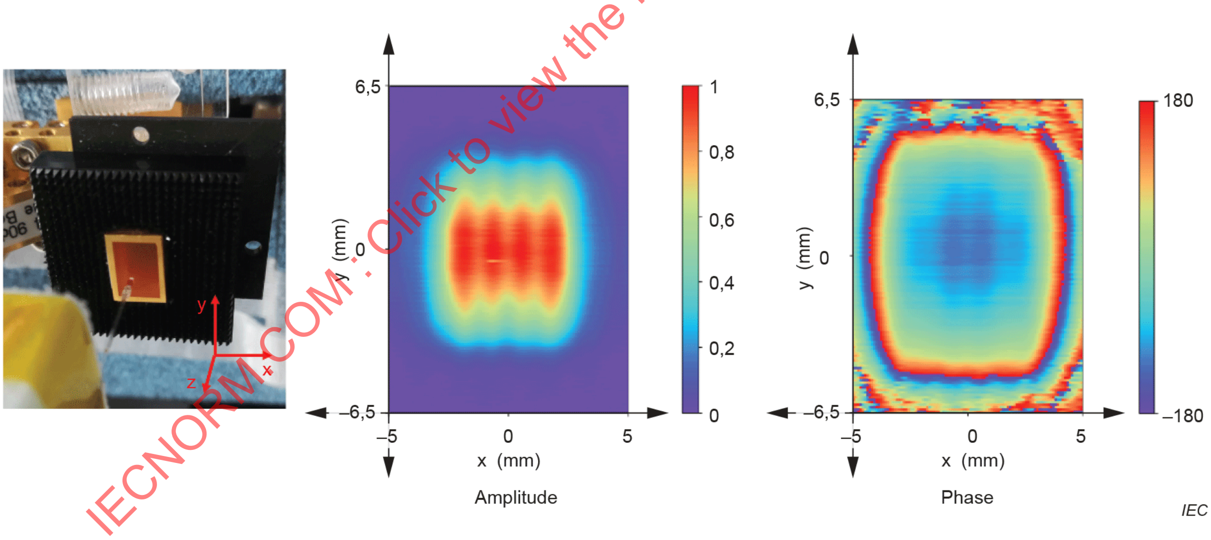


The terahertz wave is generated by the UTC-PD and emitted from the horn antenna. The horn antenna is the polygon data.

Figure 5 – Near-field of the terahertz wave (310 GHz) measured by the synchronous system based on the self-heterodyne technique

Figure 5 shows the measured near-field amplitude and phase distribution. The frequency of the terahertz wave, in this case, was 310 GHz. The horn antenna in this figure is the polygon data used in the simulation, i.e. the 3D simulation model and the 3D experimental results are put together to indicate the field. The frequency fluctuation of the RF signal was cancelled out in the self-heterodyne technique, and spatial distribution of the relative phase was mapped.

4.3.4 Near-to-far field transformation results



Amplitude and phase distributions on the antenna surface are also shown.

Figure 6 – Measured rectangular-type horn antenna and EO probe

Figure 6 shows the near-field measured on the antenna surface (XY-plane). The frequency of the terahertz wave was 288 GHz. The antenna which emitted the terahertz wave was a rectangular-type horn antenna. The black part in the photograph is the EM wave absorber. The measured surface was at Z = 2 mm from the antenna surface. The EO probe was moved by 0,1 mm pitch. The time constant of the lock-in detection was 100 ms. The maximum signal-to-ratio (SNR) was about 45 dB.

The far-field pattern was calculated based on the planner near-to-far field transformation. The simulated results were conducted based on the finite integration technique.

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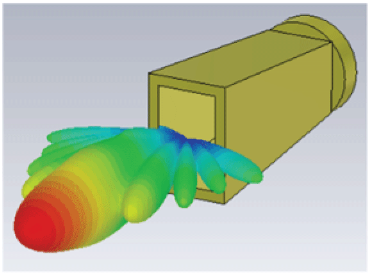
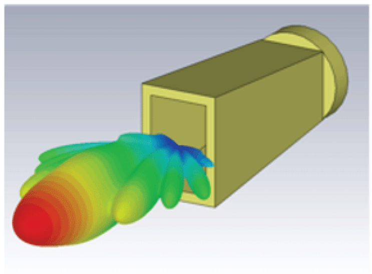


a) Simulation

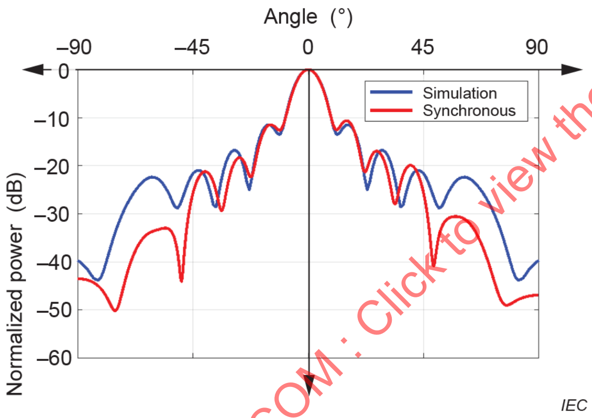


b) Experiment (synchronous)

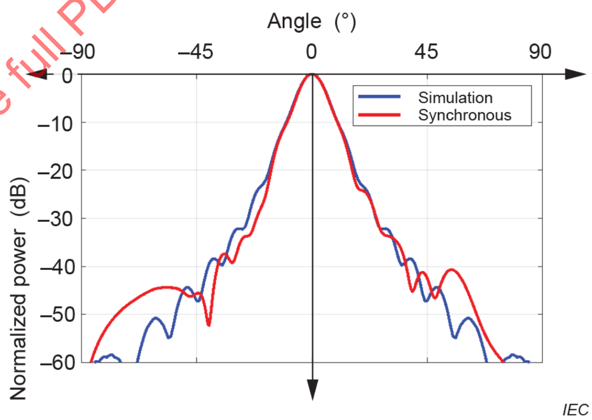
Figure 7 – Far-field pattern calculated from the near-field measured by the synchronous system

Figure 7 shows the simulated far-field pattern and calculated far-field pattern using the near-field pattern measured by the synchronous system. The horn antenna in this figure is the polygon data used in the simulation, i.e. the 3D simulation model and the 3D experimental results are put together to show the field (Figure 7 b)).

Figure 8 shows the far-field pattern in the E-plane and H-plane. The red line is based on the measured data, whereas the blue line is a simulation result. The measured far-fields agreed well with the simulated results in both planes.



E-plane



H-plane

The blue lines are the simulation results. The red lines are the calculated results using the near-field pattern measured by the synchronous system.

Figure 8 – Far-field pattern in the E-plane and H-plane

Table 1 summarizes the radiation pattern characteristics. The deviation between the simulated and measured values for the 3-dB beam width was 0,3° and 0,3° for the H-plane and E-plane, respectively. The deviation for the side lobe position was approximately 0,7° and 2,2° for the first and second side lobe in the E-plane, respectively. It is believed that those discrepancies were due to the EO probe characteristics. Probe correction might be conducted to improve the measurement accuracy.

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Table 1 – Radiation pattern characteristics measured by the synchronous system

			Simulation	Synchronous
H-plane 3 dB beam width [°]			9,7	9,4
E-plane 3 dB beam width [°]			10,2	9,9
E-plane	+ 1st side-lobe	Position [°]	15,4	14,9
		Peak to side lobe ratio [dB]	−11,4	−10,6
	− 1st side-lobe	Position [°]	−15,4	−14,7
		Peak to side lobe ratio [dB]	−11,4	−11,5
	+ 2nd side-lobe	Position [°]	28,8	26,6
		Peak to side lobe ratio [dB]	−16,7	−16,9
	− 2nd side-lobe	Position [°]	−28,8	−26,8
		Peak to side lobe ratio [dB]	−16,7	−18,3

4.4 Asynchronous system based on a phase-noise cancelling technique

4.4.1 General

The asynchronous system is a spectrum analyser type system, in which the RF signal to be measured is not supplied from the measurement system. The system generates only the LO signal to measure the amplitude and phase distribution of a near-field. The LO signals can be generated using two free-running laser diodes (LDs) or optical frequency comb (OFC). Although the relative frequency between the RF signal and LO signal fluctuates, both the amplitude and the relative phase distribution are visualized as a result of the phase-noise cancelling technique.

4.4.2 Principle and system configuration

Figure 9 shows the basic configuration of the measurement set-up. The asynchronous system consists of two parts: the non-polarimetric EO frequency down-conversion part and the phase noise-cancellation part. The non-polarimetric EO frequency down-conversion part consists of 1,55 μm telecom components. EO probe 1 can be moved for mapping, whereas EO probe 2 is fixed at the reference point for phase reference measurement. For the proof-of-concept experiment, which will be described in 4.4.3, an OFC is used for the LO signal. Each comb mode is phase-modulated by the RF signal to be measured in the EO crystal, and the sidebands are generated. An optical filter extracts one of the sidebands and the adjacent comb-mode pair, which is detected by a low-speed PD. The frequency of the intermediate frequency (IF) signal is $f_{IF} = f_2 - f_1 - f_{RF} = mf_{CS} - f_{RF}$, where m is the mode separation index, f_{CS} is the comb-mode separation, and f_{RF} is the frequency of the RF signal. The frequency of the IF signal fluctuates, reflecting the relative frequency fluctuation between the RF signal, f_{RF}, and the LO signal, mf_{CS}. On the other hand, the frequency-converted IF signal 1 and signal 2 have the same frequency fluctuations. This common-mode frequency fluctuation, more generally the common-mode phase noise, is cancelled out in the second part of the system to extract the relative phase difference of the field measured at two different points.

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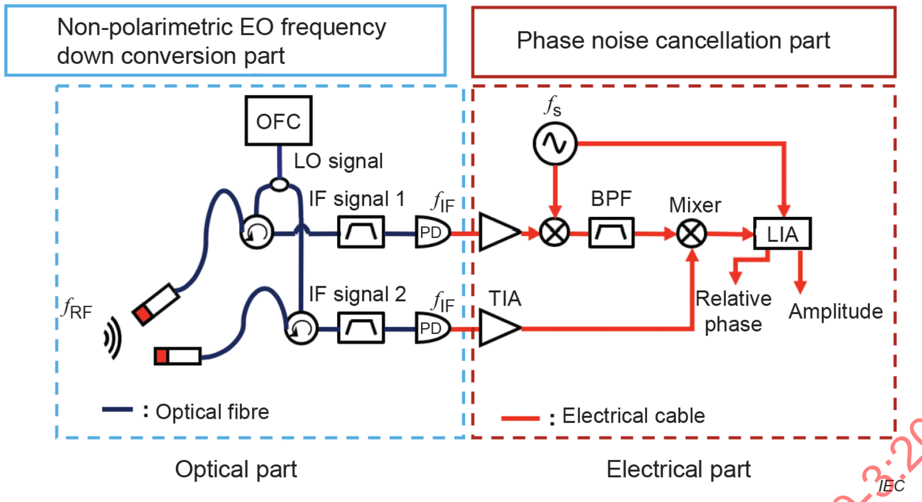

Figure 9 – Schematic diagram of the asynchronous system based on the phase noise cancelling technique

4.4.3 Example of near-field measurement

For the proof-of-concept experiment, the terahertz wave at 300 GHz band was generated with the frequency multiplier and emitted from the rectangular horn antenna. In this experiment, a 4-N, N-dimethylamino-4'-N'- methyl-stilbazolium-tosylate (DAST) crystal was used as the EO crystal. The diameter of the probe beam in the EO crystal was approximately 0,1 mm. In this proof-of-concept measurement, the RF signal was divided by a power divider, and a reference probe was set in front of port 2 of the power divider. The relative phase distribution was measured by a measurement probe.

Figure 10 shows the measured near-field amplitude and phase distribution. The frequency of the terahertz wave in this example was 288 GHz. The frequency fluctuation between the RF signal and the LO signal was cancelled out by the phase-noise-cancellation technique.

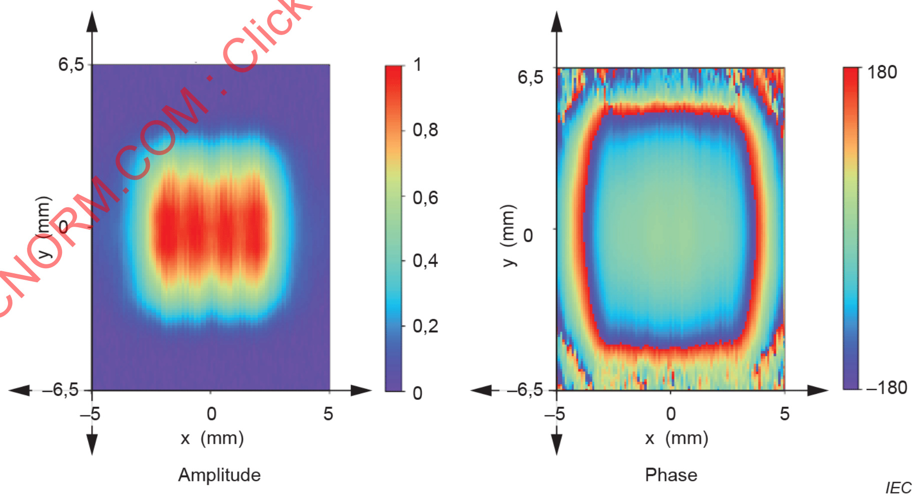

Figure 10 – Near-field pattern measured using the asynchronous system

4.4.4 Near-to-far field transformation results

Figure **11** shows the simulated and calculated far-field patterns using the near-field pattern measured by the asynchronous system. The horn antenna in this figure is the polygon data used in the simulation, i.e. the 3D simulation model and the 3D experimental results are put together to show the field (Figure **11** b)).

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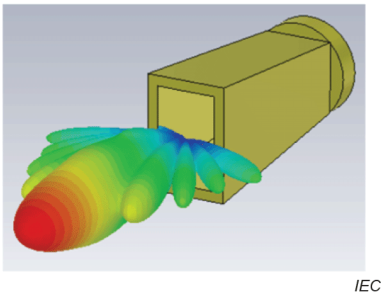
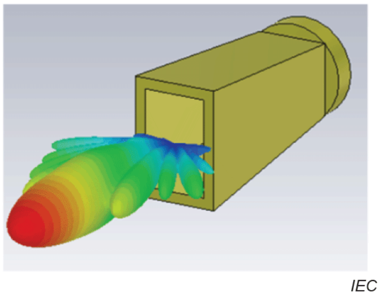
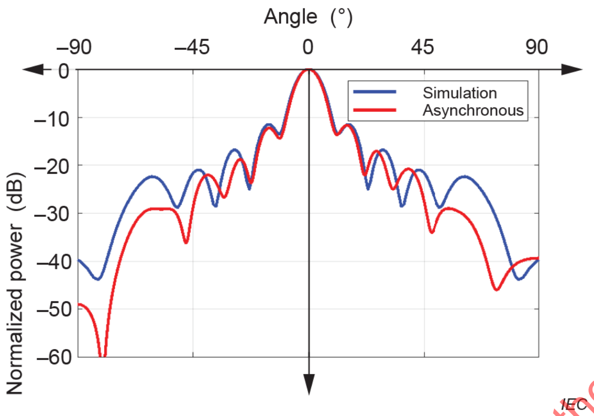


a) Simulation

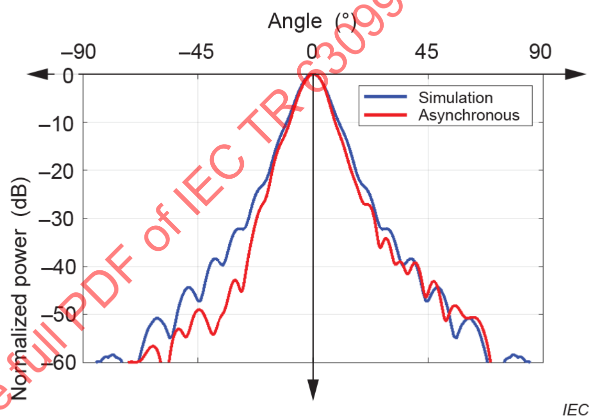


b) Experiment (asynchronous)

Figure 11 – Far-field pattern calculated from the near-field measured by the asynchronous system



E-plane



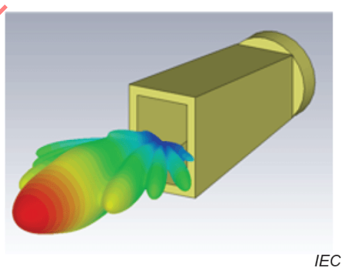
H-plane

Blue lines are simulation results. Red lines are calculated results using the near-field pattern measured by the asynchronous system.

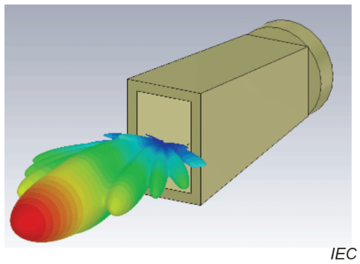
Figure 12 – Far-field pattern in the E-plane and H-plane

Figure 12 shows the far-field pattern in the E-plane and H-plane. The red line is based on the measured data, whereas the blue line is a simulation result. The measured far-fields reasonably agreed with the simulated results in both planes.

4.5 Comparison between results obtained from synchronous and asynchronous systems



a) Synchronous



b) asynchronous

Figure 13 – Far-field pattern calculated from the near-field measured by the synchronous system (a) and asynchronous system (b)

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