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INTERNATIONAL STANDARD

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Transmitting and receiving equipment for radiocommunication – Frequency response of optical-to-electric conversion device in high-frequency radio-over-fibre systems –
Part 3: Measurement method of non-linear response of optical-to-electric converter

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IEC Secretariat
3, rue de Varembé
CH-1211 Geneva 20
Switzerland

Tel.: +41 22 919 02 11
info@iec.ch
www.iec.ch

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TRANSMITTING AND RECEIVING EQUIPMENT FOR RADIOCOMMUNICATION – FREQUENCY RESPONSE OF OPTICAL-TO-ELECTRIC CONVERSION DEVICE IN HIGH-FREQUENCY RADIO-OVER-FIBRE SYSTEMS –

Part 3: Measurement method of non-linear response of optical-to-electric converter

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The text of this International Standard is based on the following documents:

Draft	Report on voting
103/270/FDIS	103/273/RVD

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The language used for the development of this International Standard 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 62803 series, published under the general title *Transmitting and receiving equipment for radiocommunication – Frequency response of optical-to-electric conversion device in high-frequency radio-over-fibre systems*, 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

A variety of photonic devices operated in microwave, millimetre-wave, and terahertz-wave bands are useful for an optical fibre transport system as well as for wireless communication and broadcasting systems. An optical-to-electric conversion device plays as an interface, which converts an optical signal into an electrical signal directly.

Microwave, millimetre-wave and terahertz-wave radio-over-fibre (RoF) systems are comprised of two parts: an electric-to-optical converter (E/O), and an optical-to-electric converter (O/E). Radio waves are converted into an optical signal at the E/O, and the signal is transferred through the optical fibre, and then the radio waves are regenerated at the O/E.

A variety of photonic devices which carry microwave, millimetre-wave, and terahertz-wave signals at subcarrier frequencies are used for high-frequency RoF systems. In advanced radio wireless communication systems, orthogonal frequency domain multiplexing and multi-level modulation techniques have been implemented for the enhancement of spectral efficiency. Even in high-frequency wireless systems in the millimetre-wave and terahertz-wave bands, high spectral efficiency modulation and demodulation formats are indispensable. These advanced modulation formats require a high linearity in devices and transmission lines, and therefore, the high-frequency RoF system should also have high linearity to transfer these radio signals. Particularly in optical-to-electric converters, non-linear distortions directly affect the quality of regenerated radio signals, to be compliant with radio regulations. Therefore, the non-linear response of the optical-to-electric converter is a key characteristic to specify result signal quality. This document defines the measurement method of a non-linear response, which has a significant impact on the performance of RoF systems.

TRANSMITTING AND RECEIVING EQUIPMENT FOR RADIOCOMMUNICATION – FREQUENCY RESPONSE OF OPTICAL-TO-ELECTRIC CONVERSION DEVICE IN HIGH-FREQUENCY RADIO-OVER-FIBRE SYSTEMS –

Part 3: Measurement method of non-linear response of optical-to-electric converter

1 Scope

This part of IEC 62803 specifies the measurement method of the non-linear response of optical-to-electric converters in both optical signal transport systems and RoF systems. The method applies for the following:

– frequency range: up to 170 GHz;
– wavelength band: 0,8 µm to 2,0 µm.

2 Normative references

There are no normative references in this document.

3 Terms, definitions and abbreviated terms

3.1 Terms and definitions

For the purposes of this document, the following terms and definitions apply.

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

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

3.1.1
3rd order intercept point
IP3
crossing point of output powers, which depend on the input optical signal power, at a frequency which is the same as the input frequency and at a frequency which is triple the input frequency

3.2 Abbreviated terms

DFG	difference frequency generation
DSB	double side-band
DSB-SC	double side-band suppressed-carrier
DUT	device under test
E/O	electric-to-optical converter
LD	laser diode
IMD3	3rd order inter-modulation distortion
IP3	3rd order intercept point
IIP3	input 3rd order intercept point
MZM	Mach–Zehnder interferometer-type intensity modulator
O/E	optical-to-electric converter
OIP3	output 3rd order intercept point
PD	photodiode
PN	positive-negative
RF	radio frequency

4 Optical-to-electric converters

4.1 Photodiode (PD)

4.1.1 General

A PD has a positive-negative (PN) junction which can be illuminated by an optical signal. When a photon is incident to the PN junction, an electron is excited, and an electron-hole pair is generated. The electron and hole drift to the opposite direction because of the built-in and reverse-biased voltage at the PN junction and can be used as an output electric current.

4.1.2 Component parts

The O/E converters consist of basic parts as follows:

- PD;
- input fibre pigtail (where appropriate);
- input receptacle (where appropriate);
- output RF port (where appropriate);
- bias electrode (where appropriate);
- transimpedance amplifier (where appropriate);
- impedance matching

4.1.3 Structure

The structure consists of the following (see Figure 1):

- optical input: fibre pigtail or receptacle;
- RF output: coaxial connector, microstrip line, coplanar waveguide, antenna, etc.;
- options: bias electrode, transimpedance amplifier, impedance-matching resistor.

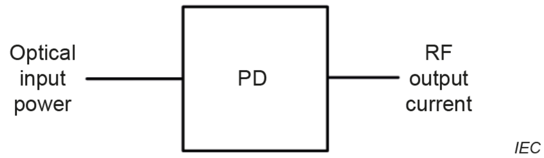


Figure 1 – Optical-to-electrical conversion by photo diode

4.1.4 Specification of PD

4.1.4.1 General

This method is based on a heterodyne principle. The materials that should be used for the PD of this measurement method are specified in 4.1.4.2.

4.1.4.2 Material of PD

The main materials of the PDs should be Si, Ge, GaAs, and InGaAs.

4.2 DFG device

4.2.1 General

When two coherent lightwaves are incident to a DFG device fabricated from a second order non-linear optical material, an RF signal with the difference frequency between the incident lightwaves is generated.

4.2.2 Component parts

The component parts are as follows:

– DFG device;
– input optical lens (where appropriate);
– output RF antenna (where appropriate).

4.2.3 Structure

See Figure 2.

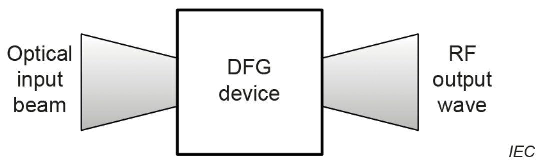


Figure 2 – DFG device

4.2.4 Specification of DFG device

4.2.4.1 General

This method is based on the heterodyne principle. The materials that should be used for the PD of this measurement method are specified in 4.2.4.2 and 4.2.4.3.

4.2.4.2 Material of DFG device

The main substrate materials of the DFG device should be materials such as $LiNbO_3$, $LiTaO_3$, KH_2PO_4, PZT (Pb (Zr, Ti) O_3), PLZT ((Pb, La) (Zr, Ti) O_3), InP, GaAs, InGaAs, InAlAs, InGaAsP, chromophore containing polymer, which realize a second order, non-linear optical effect.

4.2.4.3 Device design

In general, the efficiency of the DFG is rather low. In order to enhance the conversion efficiency, the device length tends to be long, and phase matching conditions shall be satisfied. Moreover, in order to avoid undesired RF wave radiation, an RF cavity or guiding structure is also required.

5 Sampling for quality control

5.1 Sampling

A statistically significant sampling plan shall be agreed upon between the user and supplier. Sampled devices shall be randomly selected and representatives of production population shall satisfy the quality assurance criteria using the proposed test methods.

5.2 Sampling frequency

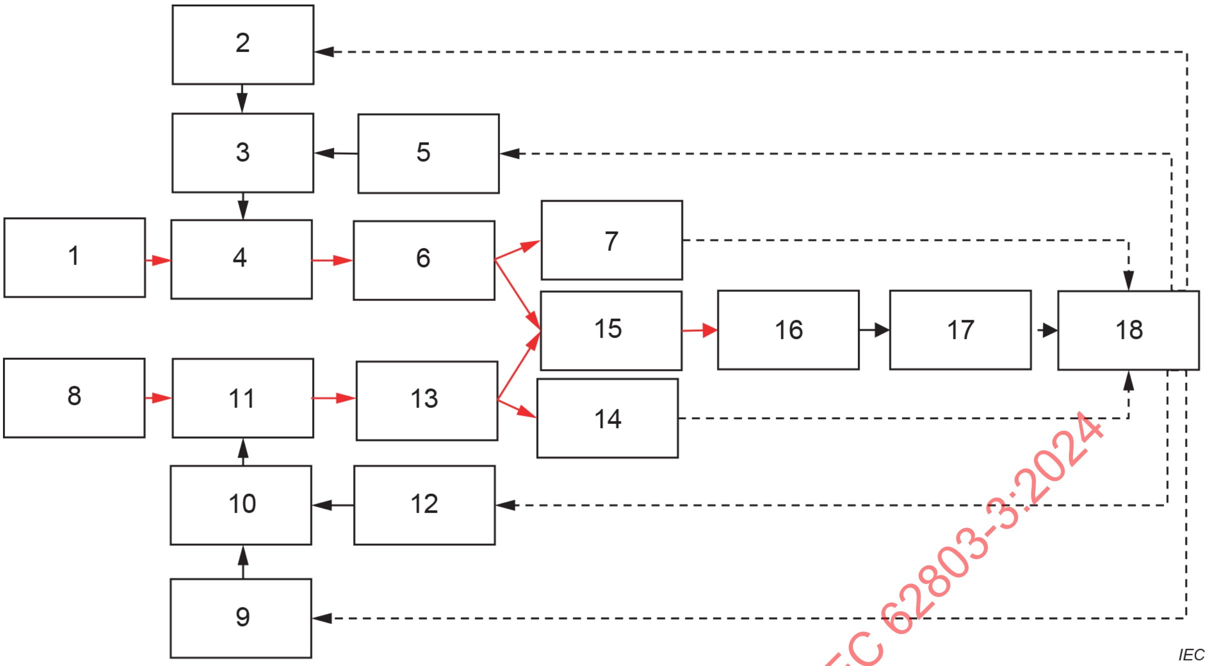
The appropriate statistical methods shall be applied to determine adequate sample size and acceptance criteria for the considered lot size. In the absence of more detailed statistical analysis, the following sampling plan can be employed.

Non-linear response: two units at least per manufacturing lot.

6 Measurement method of non-linear response

6.1 Circuit diagram

See Figure 3.



Key

1 laser diode 1

2 DC voltage source 1

3 bias tee 1

4 optical Mach-Zehnder interferometer-type intensity modulator 1

5 microwave signal source 1

6 optical attenuator 1

7 optical power meter 1

8 laser diode 2

9 DC voltage source 2

10 bias tee 2

11 optical Mach-Zehnder interferometer-type intensity modulator 2

12 microwave signal source 2

13 optical attenuator 2

14 optical power meter 2

15 optical power combiner

16 device under test

17 electrical spectrum analyser

18 personal computer

Red solid arrows = optical fibre cable

Black solid arrows = electrical wire cable

Black dashed arrows = interconnection cable

Figure 3 – Circuit diagram

6.2 Circuit description and requirements

The circuit description and requirements are given in the key to Figure 3.

6.3 Measurement conditions

6.3.1 Temperature and environment

The measurement should be carried out in a room with a temperature ranging from 5 °C to 35 °C. If the operation temperature ranges of the measurement apparatus are narrower than the above range, the specifications of the measurement apparatus should be followed. It is desirable to control the measurement temperature within ±5 °C in order to suppress the influence of the temperature drift of the measurement apparatus to a minimum. The temperature of the DUT can be changed using a temperature controller to verify the temperature dependence of the measured parameters, as necessary.

6.3.2 Warming-up of measurement equipment

The warming-up time shall be kept to typically 60 min, or the time written in the specifications of the measurement equipment or systems. Moreover, the warming-up time should be taken to be the longest among all the measurement equipment.

6.4 Principle of measurement method

6.4.1 General

The method described here is based on the heterodyne principle. Two two-tone lightwave signals with frequency separations of $\omega_{\mathrm{RF}} - \Delta$ and $\omega_{\mathrm{RF}} + \Delta$, whose symbols are denoted in 6.4.2, induces frequency downconversion in the O/E. In an ideal case, the O/E provides just two frequency components. The non-linear effect in the O/E, actually, causes a number of the frequency downconversion processes as well as the frequency upconversion processes. Finally, unwanted frequency components are generated near the frequency of the wanted signal component. The 3rd order non-linear process is based on a lowest non-linear process for provision of the signal near the wanted signal. The ratio of wanted and unwanted components and the critical point (intercept point, see Figure 4) of the plot of the input (optical) and output (electrical) wanted and unwanted signals show a fundamental characteristic of the O/E converter for signal conversion without significant non-linear effects.

6.4.2 Mathematical expressions of basic measurement principle

As is well known, an optical output from a Mach-Zehnder-interferometer-type optical intensity modulator (MZM), which is utilized as a two-tone lightwave signal generator, with a monotone RF signal modulation can be expressed by

$$E = \sum_{n=-\infty}^{\infty} E_n e^{i(\omega_n t + \phi_n)} \text{ and } \omega_{\mathrm{RF}} = \omega_{n+1} - \omega_n, \qquad (1)$$

where E and ω_{RF} denote an electric field of the optical signal and an angular frequency of the modulating RF signal that corresponds to the angular frequency difference between adjacent optical tones, respectively. The two-tone lightwave signal generation by the MZM under a bias voltage set to a minimum transmission point in the interferometer transfer function has the following relationships:

$$|E_{-1}| = |E_1| \gg |E_n| \ (n \neq \pm 1), \text{ and} \qquad (2)$$

$$E_n \propto J_n\left(A_{\mathrm{RF}}\right) e^{i\left(\omega_0 - (-1)^n \omega_{\mathrm{RF}}\right)t + i\phi_0} \ (n = 1, -1) \qquad (3)$$

where J_n, A_{RF}, ω_0, and ϕ_0 denote a Bessel function, an amplitude coefficient of the monotone RF signal at a frequency of ω_{RF}, an angular frequency of the lightwave input into the modulator, and a relative phase of the lightwave signal input into the modulator, respectively.

In the method, two two-tone lightwaves with the angular frequency of $\omega_{RF} - \Delta$ and $\omega_{RF} + \Delta$ are input into a DUT via the coupler with the expression of

$$J_{-1}(A_1)e^{i\left(\omega_1 - \frac{\omega_{RF}-\Delta}{2}\right)t} + E_{1c}e^{i\omega_1 t} + J_1(A_1)e^{i\left(\omega_1 + \frac{\omega_{RF}-\Delta}{2}\right)t} = E_{1c}e^{i\omega_1 t} + 2ie^{i\omega_1 t}E_{1s}\sin\frac{\omega_{RF}-\Delta}{2}t \quad \text{and} \tag{4}$$

$$J_{-1}(A_2)e^{i\left(\omega_2 - \frac{\omega_{RF}+\Delta}{2}\right)t} + E_{2c}e^{i\omega_2 t} + J_1(A_2)e^{i\left(\omega_2 + \frac{\omega_{RF}+\Delta}{2}\right)t} = E_{2c}e^{i\omega_2 t} + 2ie^{i\omega_2 t}E_{2s}\sin\frac{\omega_{RF}+\Delta}{2}t \tag{5}$$

where ω_1, ω_2, E_{1c}, E_{2c}, E_{1s}, E_{2s} denote angular frequencies of laser lightwaves 1 and 2, electrical fields at a carrier frequency of laser lightwaves 1 and 2, and electrical fields at a sideband component of laser lightwaves 1 and 2, respectively. In general, the O/E converts an optical power $P_{opt} \propto |E|^2$ into an electrical power P_{ele} with a conversion efficiency γ by an expression of $P_{ele} = \gamma\, P_{opt}$. Therefore, the output signal from each two-tone lightwave can be expressed by

$$\gamma\left|E_{nc}e^{i\omega_n t} + 2ie^{i\omega_n t}E_{ns}\sin\frac{\omega_n}{2}t\right|^2 \tag{6}$$

In the RF domain, the frequency components can be proportional to

$$|E_{nc}^2 - 4E_{ns}^2| + 4E_{nc}E_{ns}\sin\frac{\omega_n}{2}t + 2E_{ns}^2\cos\omega_n t \tag{7}$$

at a DC frequency, $\frac{\omega_n}{2}$, and ω_n.

The output signal by the 3rd order non-linear effect is caused by three lightwave inputs expressed by

$$\chi^{(3)}P_1P_2P_3, \tag{8}$$

where $\chi^{(3)}$ and P_n denote a 3rd order non-linear coefficient and the input lightwaves, respectively. In this case, the resultant frequency component using $P_n \propto \cos \omega_n t$ can include $|\omega_1 + \omega_2 + \omega_3|$, $|\omega_1 + \omega_2 - \omega_3|$, $|\omega_1 - \omega_2 + \omega_3|$, $|\omega_1 - \omega_2 - \omega_3|$, and $|-\omega_1 + \omega_2 + \omega_3|$. In this two two-tone lightwaves case, the signal is comprised of four components at frequencies of $\frac{\omega_{\text{RF}} - \Delta}{2}$, $\frac{\omega_{\text{RF}} + \Delta}{2}$, $\omega_{\text{RF}} - \Delta$, and $\omega_{\text{RF}} + \Delta$. From Equation (7), the frequency component of $\frac{\omega_{\text{RF}} - \Delta}{2}$ and $\frac{\omega_{\text{RF}} + \Delta}{2}$ is proportional to the carrier power. In the DSB-SC modulation based on the assumption of $E_n << E_{n\text{s}}$, the frequency component of $\frac{\omega_{\text{RF}} - \Delta}{2}$ and $\frac{\omega_{\text{RF}} + \Delta}{2}$ can be negligible. Thus, the 3rd order non-linear effect can produce the components in the RF domain expressed by:

$$\begin{aligned}&\chi^{(3)}\left(4E_{1\text{s}}^4\cos^2(\omega_{\text{RF}} - \Delta)t\ 2E_{2\text{s}}^2\cos(\omega_{\text{RF}} + \Delta)t + 4E_{2\text{s}}^4\cos^2(\omega_{\text{RF}} + \Delta)t\ 2E_{1\text{s}}^2\cos(\omega_{\text{RF}} - \Delta)t\right)\\&= \chi^{(3)}\left(16E_{1\text{s}}^4E_{2\text{s}}^2(\cos(3\omega_{\text{RF}} - \Delta)t - \cos(\omega_{\text{RF}} - 3\Delta)t - \cos(\omega_{\text{RF}} + \Delta)t\right)\\&+16E_{2\text{s}}^4E_{1\text{s}}^2\left(\cos(3\omega_{\text{RF}} + \Delta))t - \cos(\omega_{\text{RF}} + 3\Delta)t - \cos(\omega_{\text{RF}} - \Delta)t)\right)\end{aligned} \tag{9}$$

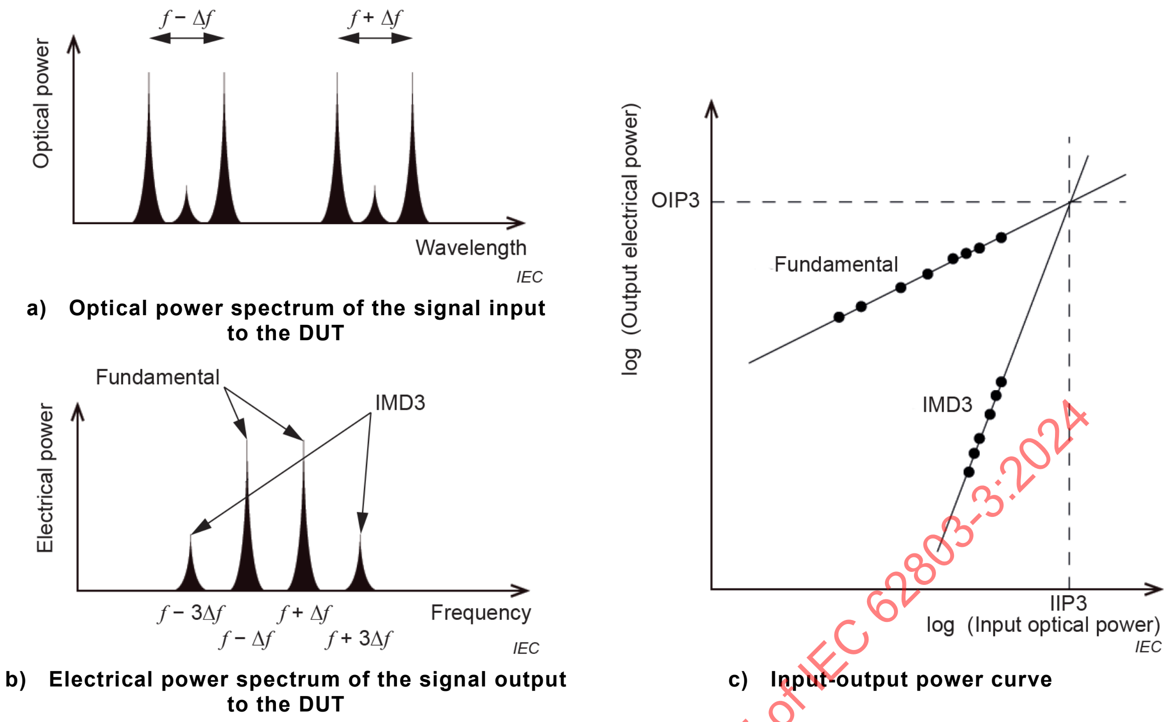
where $3\omega_{\text{RF}} \pm \Delta$ and $\omega_{\text{RF}} \pm 3\Delta$ are 3rd order inter-modulation distortion (IMD3) components. When the input optical power of lightwaves 1 and 2 is the same i.e. $E_{1x}^2 = E_{2x}^2 = P_x^2$, the output signal including fundamental and 3rd order non-linear effect can be expressed by

$$\begin{aligned}&|P_\text{c} - 4P_\text{s}| + \left(P_\text{s} - 8\chi^{(3)}P_\text{s}^3\right)\left(\cos\left(\omega_{\text{RF}} + \Delta\right)t + \cos\left(\omega_{\text{RF}} - \Delta\right)t\right)\\&+8\chi^{(3)}P_\text{s}^3\left(\cos\left(3\omega_{\text{RF}} - \Delta\right)t + \cos\left(3\omega_{\text{RF}} + \Delta\right)t - \cos\left(\omega_{\text{RF}} - 3\Delta\right)t - \cos\left(\omega_{\text{RF}} + 3\Delta\right)t\right)\end{aligned} \tag{10}$$

Finally, the O/E produces the fundamental components, which are linearly proportional to the input power at frequencies of $\omega_{\text{RF}} - \Delta$ and $\omega_{\text{RF}} + \Delta$, and the IMD3 components, which are proportional to triple the input power at frequencies of $\omega_{\text{RF}} - 3\Delta$ and $\omega_{\text{RF}} + 3\Delta$. In the PD, as a conversion from the optical signal to the induced photocurrent is based on a square-law detection manner, the resultant electrical powers of the fundamental and IMD3 components are proportional to double and sextuple the input optical power, respectively.

6.4.3 Principle of non-linear response in optical-to-electric converters

Figure 4 shows schematic illustrations of the optical power spectrum obtained at the input to the DUT and electrical power spectrum obtained at the output of the DUT. When the input optical powers vary, the electrical power, which is observed using an electrical spectrum analyser, of the fundamental and IMD3 components also varies, as shown in Figure 4.



a) Optical power spectrum of the signal input to the DUT

b) Electrical power spectrum of the signal output to the DUT

c) Input-output power curve

Figure 4 – Schematic illustrations of optical input, electrical output, and their relationships to determine IIP3 and OIP3

6.5 Measurement procedure

STEP 1) Activate the laser diode, optical attenuators, and electrical spectrum analyser.

STEP 2) The operation wavelength of the laser diodes 1 and 2 is set with the wavelength separation larger than the measured frequency. At least two times larger than the measured frequency is favourable for the wavelength separation.

STEP 3) The DUT is set before the electrical spectrum analyser.

STEP 4) Decide on the target frequency f and frequency detuning Δf.

STEP 5) The frequencies of microwave signal sources 1 and 2 are set to $\frac{f-\Delta f}{2}$ and $\frac{f+\Delta f}{2}$, respectively.

STEP 6) The amplitudes of microwave signal sources 1 and 2 are set to double the half-wave voltage of the optical Mach–Zehnder interferometer-type intensity modulators 1 and 2, respectively.

STEP 7) The output voltages of DC power supplies 1 and 2 are set to realize the DSB-SC modulation of the optical Mach–Zehnder interferometer-type intensity modulators 1 and 2. The DSB-SC modulation can be realized by minimizing the power components at frequencies of $\frac{f-\Delta f}{2}$ and $\frac{f+\Delta f}{2}$.

STEP 8) The optical powers input into an optical coupler are set to the same value P_{OIN} by tuning optical attenuators 1 and 2. The optical power from optical attenuators 1 and 2 is monitored using optical power meters 1 and 2, respectively. Finally, the input optical power to the DUT can be $2P_{\mathrm{OIN}}$.

STEP 9) The output electrical powers P_f and P_{IMD3} at frequencies of $f \pm \Delta f$ (fundamental) and $f \pm 3\Delta f$ (IMD3), respectively, are measured using an electrical spectrum analyser.

STEP 10) Plot the output electrical powers P_f and P_{IMD3} at an input optical power to the DUT $2P_{OIN}$.

STEP 11) Change the attenuation value of optical attenuators 1 and 2. It should be noted that the optical powers should be the same.

STEP 12) Process from STEP 9) to STEP 11) within the attenuation limit.

STEP 13) Extrapolate the fitting curves of the fundamental and IMD3 components.

STEP 14) The input IP3 (IIP3) and output IP3 (OIP3) are obtained at the crossing point in the input optical power and output electrical power of the fitting curve drawn in STEP 12), respectively.

6.6 Presentation of the results

The values of IIP3 (optical power, dBm or mW) and OIP3 (electrical power, dBm or mW) obtained are plotted at the measured frequencies. Figure 5 shows an example of the frequency response of the IIP3 and OIP3. Example results and procedures are shown in Annex A.

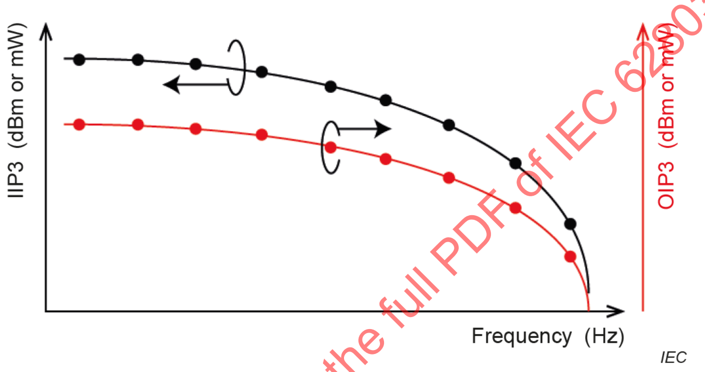


Figure 5 – Example of frequency response of IIP3 (black) and OIP3 (red)

Annex A
(informative)

Example of measurement results in a photodiode

A.1 Overview

This annex provides guidelines for the measurement of the IIP3 as a non-linear response in a photodiode.

A.2 Example of results in the measurement procedure

The optical signal launched into a photodiode is shown in Figure A.1. In this configuration, two optical signals at a centre wavelength of 1 549,68 nm and 1 549,95 nm, which corresponds to ω_1 and ω_2, respectively, are modulated with an optical Mach-Zehnder modulator at a minimum transmission point of a transfer function of the modulator. In this Figure A.1, a frequency of the signal is 3 GHz; the resultant frequency separation of the two-tone optical signal in each wavelength component is 6 GHz. This optical signal is launched into a photodiode.

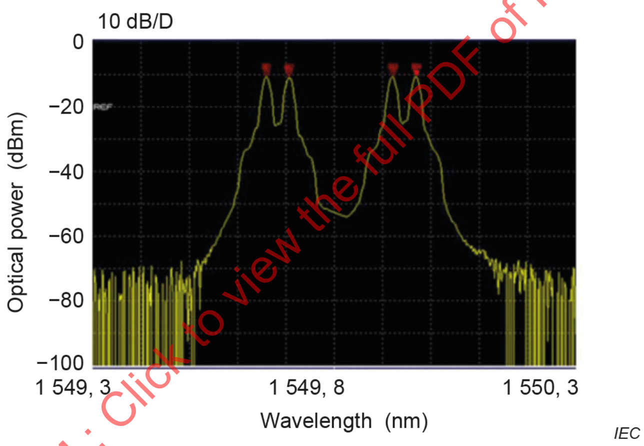


Figure A.1 – Optical spectrum of optical signals input into the photodiode

In this example, a photodiode for the application to 10 Gbit/s system is used as a device under test (DUT). Figure A.2 shows the input-output power curve at various input optical powers from −15 dBm to −6 dBm at a centre frequency f of 6 GHz. The frequency separation Δf is approximately 1 MHz and 3 MHz for circles and squares in Figure A.2. The slope of the fit line for fundamental (1st order) and 3rd order components is 2 and 6, respectively, because the photodiode is worked in a square-law detection manner. The crossing point of the extrapolation of the fundamental and 3rd order fit lines can be measured, and thus, the IIP3 obtained is 3,4 dBm.