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PUBLICLY AVAILABLE SPECIFICATION

PRE-STANDARD

Measurement method of a half-wavelength voltage for Mach-Zehnder optical modulators in wireless communication and broadcasting systems

IEC/PAS 62593:2008(E)

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CONTENTS

INTERNATIONAL ELECTROTECHNICAL COMMISSION

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MEASUREMENT METHOD OF A HALF-WAVELENGTH VOLTAGE FOR MACH-ZEHNDER OPTICAL MODULATORS IN WIRELESS COMMUNICATION AND BROADCASTING SYSTEMS

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INTRODUCTION

A variety of microwave-photonic devices are used in wireless communication and broadcasting systems. An optical modulator is an interface which converts an electronic signal into an optical signal. In the field of optical fibre communication systems, the IEC 62007 series "Semiconductor optoelectronic devices for fibre optic system applications" has been published. In the field of wireless systems, specifications of inter-modulation and composite distortion of modulators have been an important issue and have typically been negotiated between users and suppliers. During an International Meeting on Microwave Photonics, a proposal was announced to address standardizations for key-devices for Radio over Fibre (RoF) systems.

The RoF system is comprised mainly of two parts; one is the RF to photonic converter (E/O), and the other is photonic to RF converter (O/E). Radio waves are converted into an optical signal at E/O, and the signal is transferred into the optical fibre, and then the radio waves are regenerated at O/E. The nonlinear distortion characteristics of both E/O and O/E are important for the performance of the system. Semiconductor photodiodes are commonly used for O/E. Several types of optical modulator are used for E/O, such as Mach-Zehnder modulators, electro-absorption modulators and directly modulated LDs.

This PAS has been prepared in order to provide industry standard measurement methods for evaluating electro-optic material based Mach-Zehnder optical modulators to be used in wireless communication and broadcasting systems. When the optical modulation index (OMI) is calculated from the half-wavelength voltage measurement results, the intermodulation distortion of the Mach-Zehnder optical modulator can be obtained. In this PAS, the measurement method of the half-wavelength voltage for Mach-Zehnder optical modulators is described. The details of calculations of the second order intermodulation distortion (IM2) and the third order intermodulation distortion (IM3) are described in Annex B.

MEASUREMENT METHOD OF A HALF-WAVELENGTH VOLTAGE FOR MACH-ZEHNDER OPTICAL MODULATORS IN WIRELESS COMMUNICATION AND BROADCASTING SYSTEMS

1 Scope

This PAS gives a measurement method of half-wavelength voltage applicable to Mach-Zehnder optical modulators in wireless communication and broadcasting systems. In addition, this method is also effective for the estimation of the intermodulation distortion of Mach-Zehnder optical modulators.

– Frequency range: 10 MHz to 30 GHz.
– Wavelength band: 0,8 µm, 1,0 µm, 1,3 µm and 1,5 µm.
– Electro-optic material based Mach-Zehnder optical modulators and their modules.

2 Normative references

The following referenced documents are indispensable for the application 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.

IEC 62007-1, *Semiconductor optoelectronic devices for fibre optic system applications - Part 1: Specification template for essential ratings and characteristics*

IEC 62007-2 *Semiconductor optoelectronic devices for fibre optic system applications - Part 2: Measuring methods*

3 Terms, definitions and acronyms

3.1 Terms and definitions

For the purpose of this document, the terminology concerning the physical concept, the type of devices, the general terms, those related to rating and characteristics in IEC 62007-1 and IEC 62007-2, as well as the following terms and definitions, apply.

3.1.1 Half-wavelength voltage: $V\pi$

The voltage required for a Pockels effect material based optical modulator to shift phase of the light by one-half a wavelength relative to the other. It corresponds to an ON/OFF voltage of the Mach-Zehnder optical modulator.

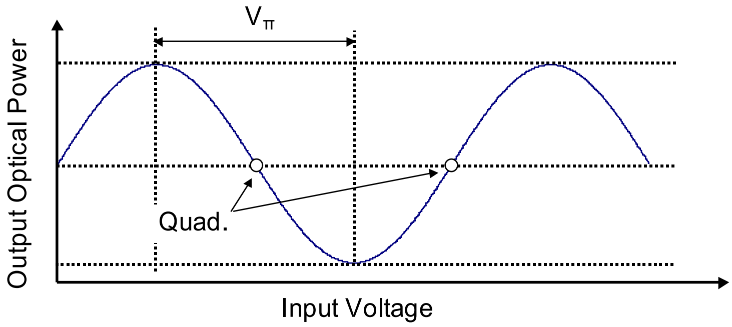

Figure 1 – A transfer curve of a Mach-Zehnder optical modulator

3.1.2 Normalized optical modulation index: NOMI

For the Mach-Zehnder optical modulator, the ratio of driving voltage and half-wavelength voltage of the modulator,

$$\text{NOMI} = (V_{pp} / V_{\pi}) \times 100\ [\%] \quad (3.1)$$

where

V_{pp} is the driving voltage (peak to peak voltage);

V_{π} is the half-wavelength voltage.

NOTE NOMI does not denote actual optical modulation index defined as the ratio of the optical modulated signal power and the average optical power. The detailed explanations of OMI including measurement method are described in Annex A.

3.1.3 Extinction Ratio

The ratio of two optical power levels of the optical signal generated by the optical modulator:

$$R_{ext} = 10\log(P_1/P_2) \quad (3.2)$$

where

P_1 is the optical power level generated when the output power is "on,";

P_2 is the power level generated when the output power is "off."

NOTE The extinction ratio is sometimes expressed as a fraction, not in dB.

3.1.4 Acronyms and symbols

The acronyms and symbols are shown in Table 3.1.

Table 1 – Acronyms and Symbols

V_{π}	A Half wavelength voltage
OMI	Optical Modulation Index
NOMI	Normalized OMI
IM2	Second-order Inter-Modulation distortion
IM3	Third-order Inter-Modulation distortion
CSO	Composite Second-Order distortion
CTB	Composite Triple-Beats distortion

4 Electro-optic material based Mach-Zehnder optical modulator

4.1 Type

The optical modulators and their modules consist of basic parts as follows

- Mach-Zehnder interferometer type optical modulator
- input and output fibre pigtails (where appropriate)
- bias control port (where appropriate)
- photodiode for bias monitoring (where appropriate)
- laser diode for light source (where appropriate)
- thermal sensor (where appropriate)
- Peltier element (where appropriate)

4.2 Structure

- Electrode: lumped type, traveling-wave type, etc.
- Options: optical isolator, photodiode, half-mirror, laser-diode, etc.

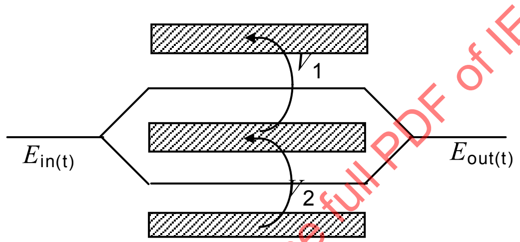

Figure 2

4.3 Requirements for Mach-Zehnder optical modulators

This method is based on the theoretical transfer curve of an electro-optic material based Mach-Zehnder interferometer, where the phase shift of traveling light on each arm of the interferometer should be proportional to the applied voltage, and power of traveling lights on each arm are almost same. Requirements for the modulator of this measurement method are as follows:

4.3.1 Substrate material

The main Substrate materials of the modulator should be the materials such as $LiNbO_3$, $LiTaO_3$, KH_2PO_4, PZT, PLZT, InP, GaAs, InGaAs, InAlAs, InGaAsP, CLD type chromophore containing polymer, FTC type chromophore containing polymer, etc., which realize an electro-optic effect (Pockels effect). If strictly considered, semiconductor materials do not have pure electro optic effect, however, the semiconductor Mach-Zehnder modulators can be adjudged as electro-optic material based Mach-Zehnder modulators.

4.3.2 Optical waveguide design

The optical waveguide should be designed as a single Mach-Zehnder interferometer type comprised of two y-junctions or symmetric directional couplers and parallel waveguides. Reflection type Mach-Zehnder optical modulators are included.

5 Sampling

5.1 Sampling

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

5.2 Sampling frequency

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.

Half wavelength voltage: two units at least/manufacturing lot.

6 Measurement method of half wavelength voltage

6.1 Circuit diagram

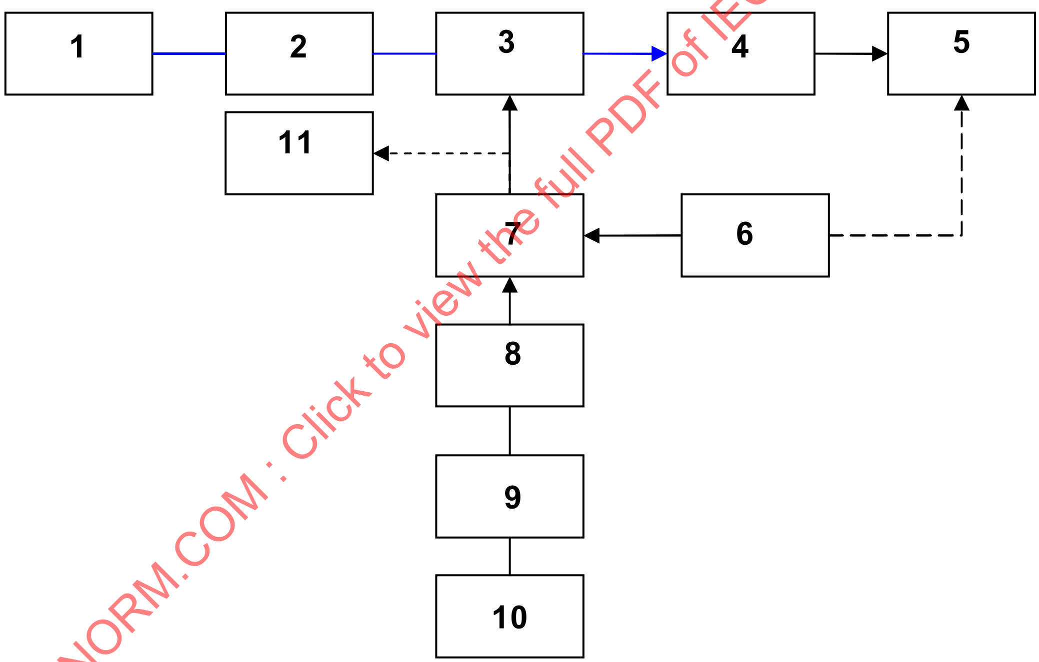

Figure 3 – Circuit diagram

6.2 Circuit description and requirement

1 = Laser diode
2 = Polarization controller
3 = Device Under Test
4 = Photo Diode
5 = Oscilloscope
6 = Monitor Signal Source (SG2)
7 = Bias Tee
8 = (Step) Attenuator (Electrical)
9 = Microwave Amplifier
10 = Microwave Signal Source (SG1)
11 = Power Meter or Spectrum Analyzer (electrical)

6.3 Measurement condition

6.3.1 Temperature and environment

The measurement should be carried out in the room 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 measurement apparatus to minimum.

6.3.2 Warming up of measurement equipment

The warming-up time shall be respected, typically 60 minutes, or the time written in the specifications of the measurement equipments or systems. Moreover, the warming up time should be that of to be the longest of all the measurement equipment.

6.4 Principle of measurement method

The Method for measuring half-wavelength voltage (AC half-wavelength voltage) of a Mach-Zehnder type optical modulator is described here. In this method, the half-wavelength voltages of Mach-Zehnder type optical modulators can be measured accurately without depending on the bias voltage of an optical modulator. When the input RF signal to the modulator is set to such a specific level that the zero-order Bessel function can be zero, the average optical output power of the modulator becomes constant regardless of the bias voltage. By measuring the input RF power or voltage at this condition, half-wavelength voltage, V_π is determined. This measurement can be achieved through a wide frequency range, though it needs a high-voltage signal source (of about 1,5 times of $V\pi$).

6.4.1 Measurement principle

The optical output power of MZ modulators is given by,

$$I = \frac{I_0}{2}\left[1+\cos(\Phi_1+\Phi_2)\right] \qquad (6.1)$$

$$\Phi_1 = \frac{\pi V_{pp}}{2V_\pi}\sin(2\pi f t) \qquad (6.2)$$

$$\Phi_2 = \text{const.} \qquad (6.3)$$

where $\phi 1$ and $\phi 2$ are the phase change caused by the high-frequency RF signal and that due to the Bias voltage, respectively. V_π is the half-wavelength voltage at the RF signal frequency f, V_{pp} is the peak-to-peak voltage amplitude of the high-frequency wave, and I_0 is the maximum optical output power. The time average power of I, I' is calculated by,

$$\begin{aligned} I' &= f\int_0^{1/f}\frac{I_0}{2}\left[1+\cos(\Phi_1+\Phi_2)\right]dt \\ &= f\int_0^{1/f}\frac{I_0}{2}\left[1+\cos\Phi_1\cos\Phi_2-\sin\Phi_1\sin\Phi_2\right]dt \end{aligned} \qquad (6.4)$$

After calculation from Eq. (6.4), we get,

$$I' = f\int_0^{1/f} \frac{I_0}{2}\left[1 + cos\left\{\frac{\pi V_{pp}}{2V_\pi} sin(2\pi ft)\right\} cos\,\Phi_2 - sin\left\{\frac{\pi V_{pp}}{2V_\pi} sin(2\pi ft)\right\} sin\,\Phi_2\right]dt$$

$$= f\int_0^{1/f} \frac{I_0}{2}\left[1 + \sum_{n=0}^{\infty}\varepsilon_n\, cos(2n\cdot 2\pi ft) J_{2n}\left\{\frac{\pi V_{pp}}{2V_\pi}\right\} cos\,\Phi_2 - \sum_{n=0}^{\infty} 2\, sin\{(2n+1)2\pi ft\} J_{2n+1}\left\{\frac{\pi V_{pp}}{2V_\pi}\right\} sin\,\Phi_2\right]dt \quad (6.5)$$

$$= \frac{I_0}{2}\left[1 + J_0\left(\frac{\pi V_{pp}}{2V_\pi}\right) cos\,\Phi_2\right]$$

where

$$\varepsilon_n = \begin{cases} 1 \cdots n = 0 \\ 2 \cdots n \neq 0 \end{cases}$$

When the input RF signal is tuned so that the relation $\pi V_{pp\ min}/(2V_\pi)$ = 2,405 can be satisfied, the zero-order Bessel term in the Eq. (6.5) becomes zero, and the time average of the optical output power becomes constant. As shown in Figure 4, there are many voltage amplitudes at which the AC component of I' goes down to zero. $V_{p\text{-}p\ min}$ denotes the lowest one of them.

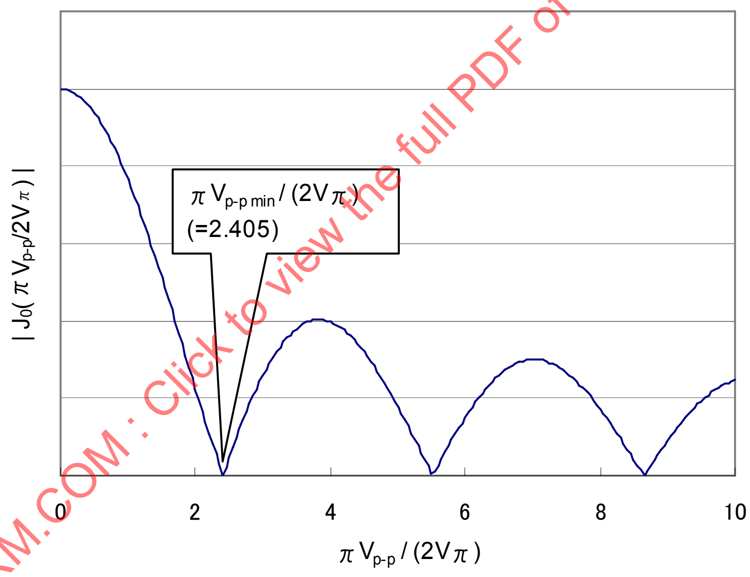

Figure 4

The schematic block diagram of the measurement setup is shown in Figure 3. In order to easily find the state where the optical output is constant, a low frequency signal for monitor (SG2) is superimposed on the RF signal. By adjusting the RF voltage amplitude of the high-frequency signal (SG1), the status can be observed where the monitor signal (SG2) amplitude shows the minimum value. At this status the wave form of monitor signal is observed as a flat line on the screen of the oscilloscope. V_π at the frequency of SG1 can be calculated from the measured result of $V_{p\text{-}pmin}$ using the following relation.

$$V\pi = \frac{\pi V_{p-pmin}}{2\times 2.405} = \frac{\pi\cdot 20(10^{(P\_S1/10-3)})^{1/2}}{2\times 2.405} \quad (6.6)$$

6.4.2 Circuit diagram

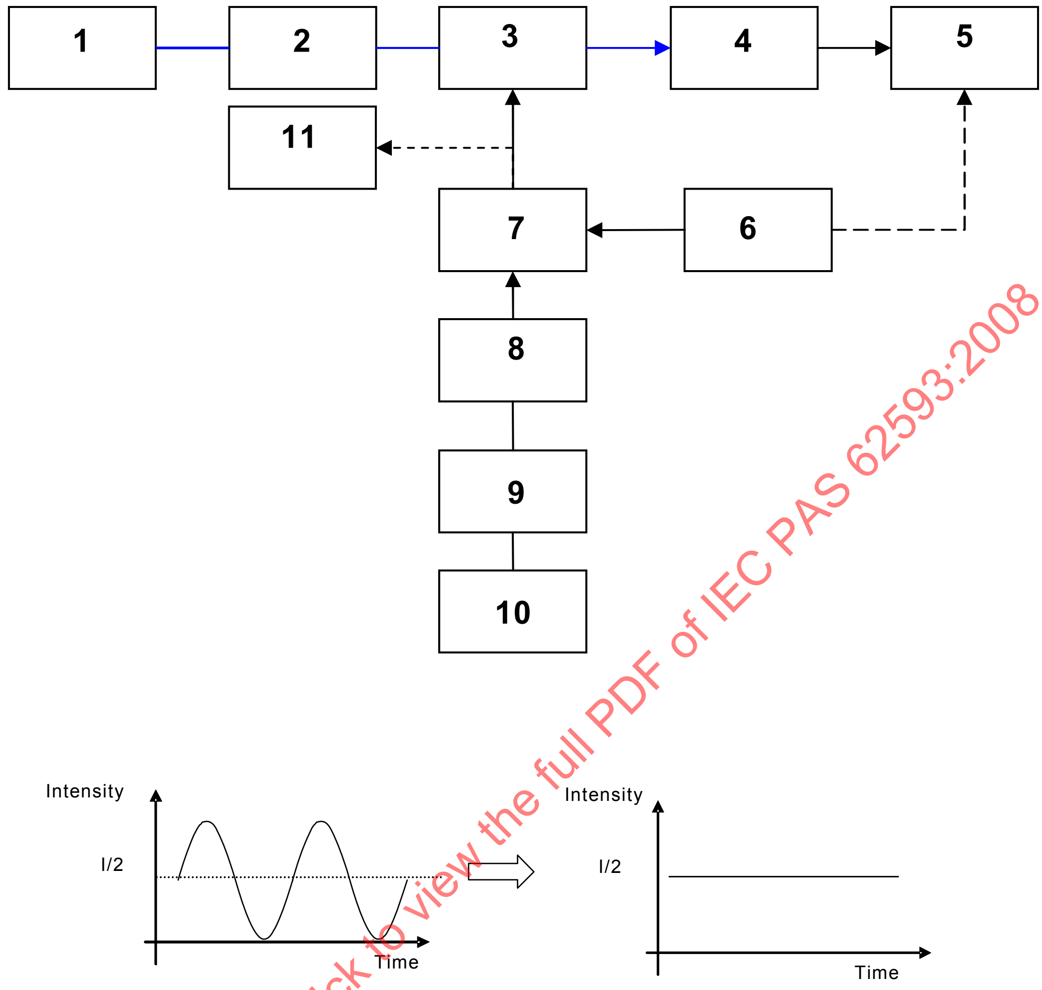

Figure 5 – The schematic block diagram of the measurement setup

6.4.3 Circuit description and requirement

1 = Laser diode
2 = Polarization controller
3 = Device Under Test
4 = Photo Diode
5 = Oscilloscope
6 = Monitor Signal Source (SG2)
7 = Bias Tee
8 = (Step) Attenuator (Electrical)
9 = Microwave Amplifier
10 = Microwave Signal Source (SG1)
11 = Power Meter or Spectrum Analyzer (electrical)

According to this method, by only measuring the minimum value $V_{\text{p-p min}}$ of the voltage amplitude of the high-frequency AC signal when the intensity change of an output light related to the monitoring low-frequency AC signal is almost zero, the half-wavelength voltage V_π of a Mach-Zehnder type optical modulator can be measured easily. In addition, if the frequency under test is a high frequency, since there is no need to observe high-frequency waveform directly, accurate measurement is possible. At the same time, because this is not a measurement method which depends on a bias point, there is no need to adjust the bias point, and there is no effect from bias point variation of the optical modulator.

6.5 Measurement procedure

STEP 1) The measurement setup is prepared as shown in Figure 6.

STEP 2) The output signals of S.G.1 and S.G.2 (abbreviated to S1 and S2, respectively) are set as follows:

S1 (initial setting conditions)

Frequency: measurement frequency of driving voltage (800 MHz, 801 MHz, etc)

Output power: ≤ 0 dBm (0,6 $V_{\text{p-p}}$) at Point-a

S2 (initial setting conditions)

Frequency: 1-tone to be selected from the range of 1 kHz - 2 MHz

Output power: ≤ 1 – 5 $V_{\text{p-p}}$ at Point-a

STEP 3) The DC voltage applied to the LN modulator can be controlled both manually and automatically (it is not necessary to adjust the DC voltage).

STEP 4) The waveform of Ch2 detected by PD is displayed in the oscilloscope. The overlapped waveform of Ch1 is also simultaneously displayed.

STEP 5) When the power of S1 is continuously increased, the amplitude of Ch2 modulated by the S2 element periodically becomes almost zero (see Figure 8). The first S1 power (at Point-a) to make the amplitude almost zero is measured by the power meter and $V\pi$ is calculated.

The half wave length voltage can be obtained from the measured S1 power (at Point-a), P_S1 , by using the following formula.

$$V\pi = \frac{\pi V_{p-p\,\min}}{2 \times 2{,}405} = \frac{\pi 20(10^{(P\_S1/10-3)})^{1/2}}{2 \times 2{,}405} \qquad (6.7)$$

NOTE Modified circuit diagram is shown in Figure 7. In this case, a power divider is used instead of an attenuator and re-connection of the modulator to the power meter is not required for measurement of RF-Power of point A. The power of point A should be calibrated according to the power ratio between point A and B.

6.5.1 Circuit diagram (Type A)

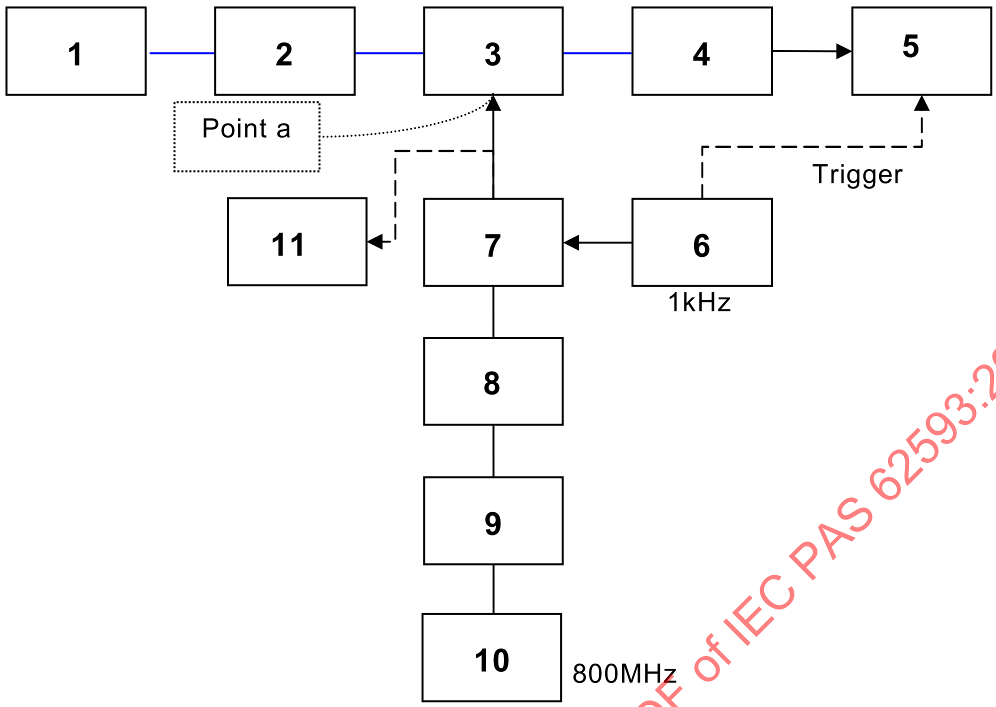

Figure 6 – Driving voltage measurement setup

6.5.2 Circuit description and requirement

1 = Laser diode
2 = Polarization Controller
3 = Device Under Test
4 = Photo Diode
5 = Oscilloscope (electrical)
6 = Signal Source (LF)
7 = Bias Tee
8 = Step Attenuator
9 = Microwave Amplifier
10 = Microwave Signal Source
11 = Power meter

6.5.3 Circuit diagram (Type B)

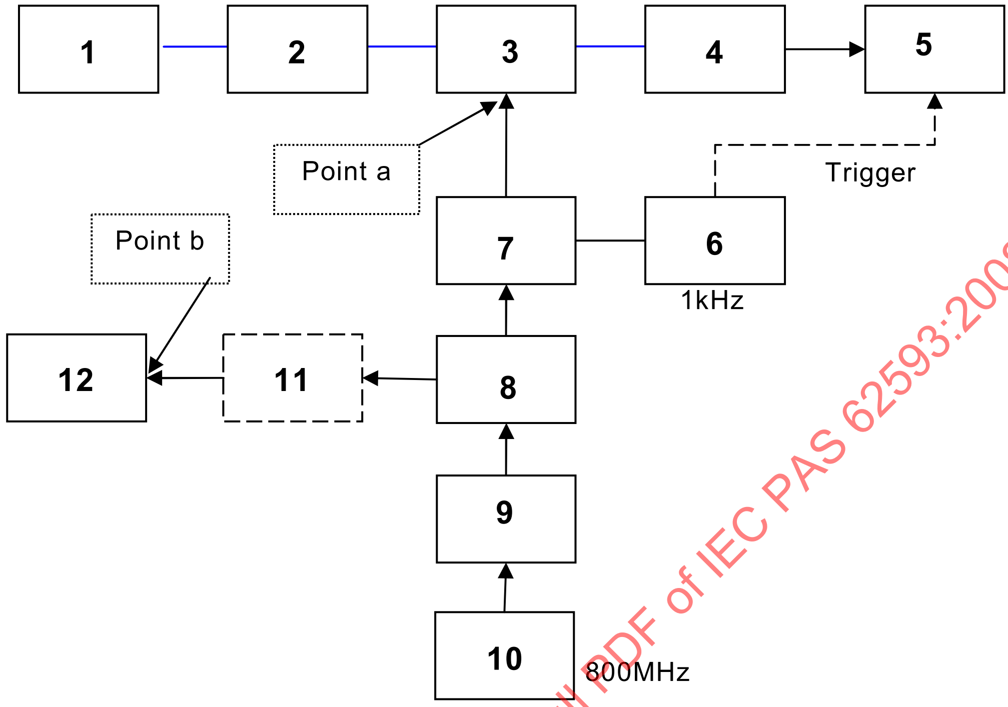

Figure 7

6.5.4 Circuit description and requirement

1 = Laser diode
2 = Polarization Controller
3 = Device Under Test
4 = Photo Diode
5 = Oscilloscope (electrical)
6 = Signal Source (LF)
7 = Bias Tee
8 = Power divider
9 = Microwave Amplifier
10 = Microwave Signal Source
11 = Attenuator
12 = Power meter

Figure 8 – The amplitude of the optical signal is almost zero

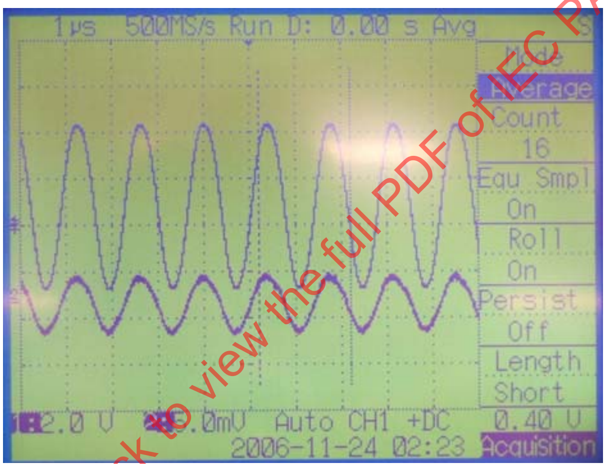

Figure 9 – The optical signal is modulated in phase with S2 element

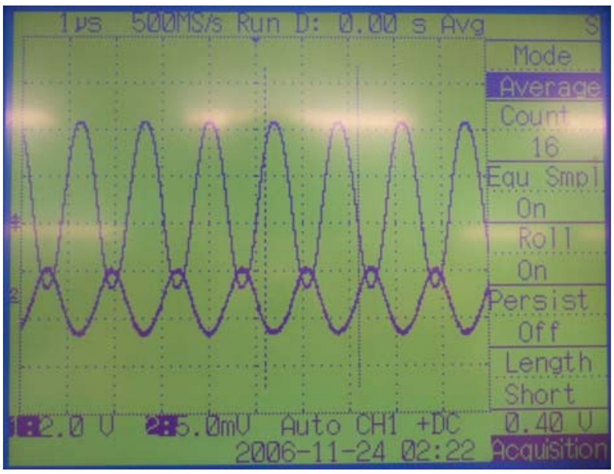

Figure 10 – The optical signal is modulated in opposite phase with S2 element

Annex A
(normative)

Conventional Measurement method of Optical Modulation Index

A.1 General

In this Annex, generic measurement methods of the optical modulation index (OMI) of analogue optical modulator under specified modulation conditions are described. For more details, IEC 62007-2

For the Mach-Zehnder optical modulator, normalized OMI (NOMI) is defined as the following formula;

$$\text{NOMI} = (V_{pp} / V\pi) \times 100 \, [\%]$$

and easily obtained by calculation from the measurement result of half-wavelength voltage.

A.1.1 Circuit diagram

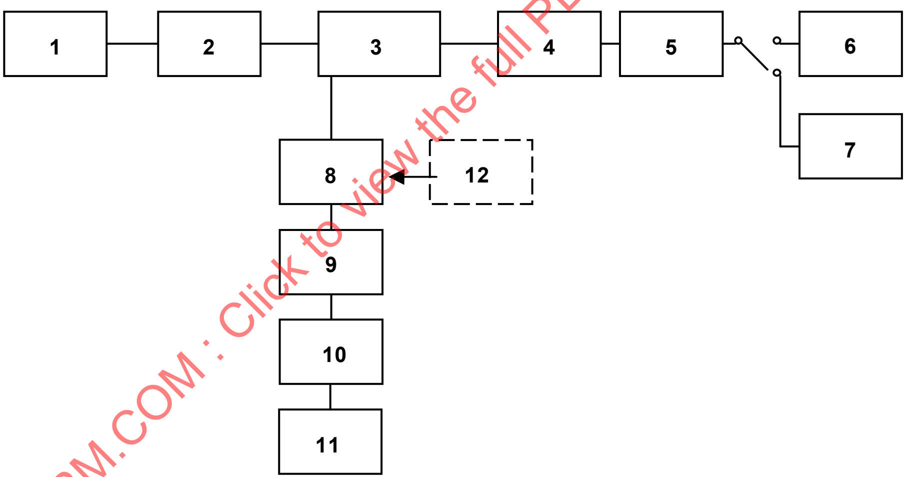

Figure A.1

A.1.2 Circuit description and requirement

1 = Laser diode
2 = Polarization Controller
3 = Device Under Test
4 = Photo Diode
5 = DC Block
6 = Oscilloscope (electrical)
7 = Power meter
8 = Bias Tee
9 = (Step) Attenuator (Electrical)
10 = Microwave Amplifier
11 = Microwave Signal Source (RF1)
(12 = DC Bias Source)

A.2 Measurement procedures

A.2.1 Spectrum Analyzer Method

A device under test is modulated with a single RF frequency by signal source, S_k. The optical output is coupled to the detector input. The detector is appropriately biased with the DC source. A current meter is used to measure the average photocurrent I_{ph}. The detector is impedance matched to the measurement equipment. The signal current amplitude can be determined from the power P at one of the modulation frequency detected by the spectrum analyzer or RF power meter.

The optical modulation index can be calculated with:

$$OMI = (2\ P_w\ /\ R)^{1/2}\ /\ I_{ph} \tag{A.1}$$

where

P_w is the detected electrical power in watts,

R is the load resistor in ohm (matched to the impedance of the spectrum analyzer or power meter)

I_{ph} is the average photocurrent in amperes.

A.2.2 Oscilloscope Method

An optical modulator is modulated with a single RF frequency by signal source, S_k. The impedance matched photo diode (PD) is now DC-coupled to an oscilloscope through R. The transfer curve of the modulator can be observed, as illustrated in Figure A.2,. The optical modulation index can be calculated with:

$$OMI = (\ i_{max} - i_{min})\ /\ (\ i_{max} + i_{min}) = i\ /\ i_{av} \tag{A.2}$$

where

i_{max} is the maximum signal current (per carrier);

i_{min} is the minimum signal current;

i is the signal current amplitude;

i_{av} is the average signal current.

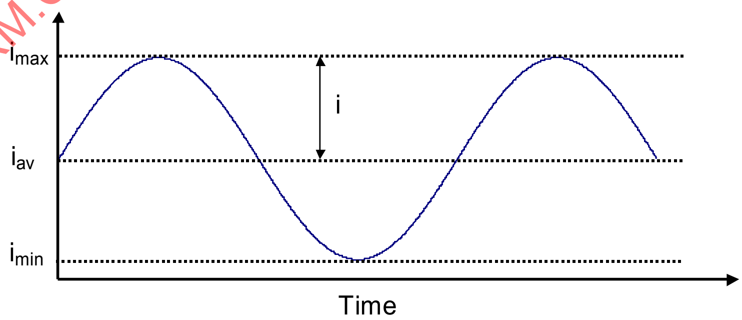

Figure A.2

In this method, an oscilloscope corresponding to the signal frequency is required. The photo diode (PD) should correspond to the signal frequency. The input optical power to the PD should be kept within the line response range of PD.

Annex B
(informative)

Calculation method of intermodulation distortions from driving voltages and half-wavelength voltage for Mach-Zehnder optical modulator

B.1 General

This PAS shows the method of calculating the amount of intermodulation from optical modulation index defined as the ratio of driving voltage and half-wavelength voltage for the Mach-Zehnder optical modulator. For reference, conventional measurement methods of the second-order inter-modulation distortion (IM2) and the third-order inter-modulation distortion (IM3) of optical modulators under specified modulation conditions are shown.

B.2 Explanation of calculation method

When the amount of optical modulation index (OMI) is calculated from the half-wavelength voltage measurement results, the intermodulation distortion (IMD) of the Mach-Zehnder optical modulator can be obtained. The details of calculations of second order intermodulation distortion (IM2) and third order intermodulation distortion (IM3) are described in the following.

The multi carrier signals are input to a Mach-Zehnder optical modulator as shown in Figure B.1.

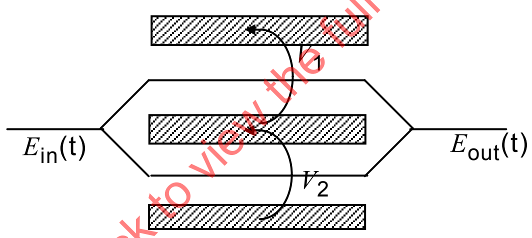

Figure B.1 Mach-Zehnder interferometer type optical modulator

The signal voltages, V_1 and V_2, are expressed as ;

$$V_1 = V_{DC1} + \sum_{k=1}^{N} v_{RF} \sin(\omega_k t + \phi_{RF1}) \tag{B.1}$$

$$V_2 = V_{DC2} + \sum_{k'=1}^{N} v_{RF} \sin(\omega_k t + \phi_{RF2}) \tag{B.2}$$

$(k = 1,2,\cdots N)$

Where V_{DC1}, V_{DC2} are the input DC voltage to optical modulator, V_{RF} is a magnitude of input RF signal, ω_k is a angular frequency of k^{th} channel in FDM signal, and φ_{RF1}, φ_{RF2} are the initial phase of input RF signal. φ_{RF1} and φ_{RF2} has a relationship as:

$$\phi_{RF2} = \phi_{RF1} + \pi \tag{B.3}$$

The input optical carrier to optical modulator is assumed as

$$E_{in}(t) = \sqrt{2P_{in}}\, e^{j(\omega_0 t)} \tag{B.4}$$

where P_{in} is the optical input power to optical modulator and ω_0 is angular frequency of optical input signal. Then the optical output signal is expressed as

$$E_{out}(t) = \sqrt{P_{in} L_{opt}} \left[e^{j\{\omega_0 t + \phi_1 + v(t)\}} + e^{j\{\omega_0 t + \phi_2 + v'(t)\}} \right] \quad \text{(B.5)}$$

where L_{opt} is the optical loss of optical modulator, and

$$\phi_1 = \frac{\pi}{2} \frac{V_{DC1}}{V\pi_{DC}} \quad \text{(B.6)}$$

$$\phi_2 = \frac{\pi}{2} \frac{V_{DC2}}{V\pi_{DC}} \quad \text{(B.7)}$$

$$v(t) = m \sum_{k=1}^{N} \sin(\omega_k t + \phi_{RF1}) \quad \text{(B.8)}$$

$$v'(t) = m \sum_{k=1}^{N} \sin(\omega_k t + \phi_{RF2} + \pi) = -m \sum_{k=1}^{N} \sin(\omega_k t + \phi_{RF2}) \quad \text{(B.9)}$$

where m is the induced optical phase due to the RF input signal. When the $E_{out}(t)$ is detected by PD with its responsivity, r, output current of PD is given by

$$\begin{aligned} i(t) &= \frac{r}{2} \left| E_{out}(t) \right|^2 \\ &= \frac{1}{2} r P_{in} L_{opt} \left[2 + e^{j\{\phi_1 - \phi_2 + 2v(t)\}} - e^{j\{\phi_1 - \phi_2 + 2v(t)\}} \right] \\ &= r P_{in} L_{opt} \left[1 + \cos(2v(t) + \Delta\phi) \right] \\ &= r P_{in} L_{opt} \left[1 + \mathrm{Re} \left[e^{j\left\{ 2m \sum_{k=1}^{N} \sin(\omega_k t + \phi_{RF1}) + \Delta\phi \right\}} \right] \right] \\ &= r P_{in} L_{opt} \left[1 + \mathrm{Re} \left[e^{j\left\{ 2m \sum_{k=1}^{N} \sin\theta_k(t) \right\}} e^{j(\Delta\phi)} \right] \right] \end{aligned} \quad \text{(B.10)}$$

where

$$\Delta\phi = \phi_1 - \phi_2 \quad \text{(B.11)}$$

$$\theta_k(t) = \omega_k t + \phi_{RF1} \quad \text{(B.12)}$$

and

$$\begin{aligned} e^{j\left\{ 2m \sum_{k=1}^{N} \sin\theta_k(t) \right\}} &= \prod_{k=1}^{N} e^{j\{2m \sin\theta_k(t)\}} \\ &= \prod_{k=1}^{N} \left[\sum_{n_k=-\infty}^{\infty} J_{n_k}(2m) e^{j n_k \theta_k(t)} \right] \\ &= \sum_{n_1=-\infty}^{\infty} \sum_{n_2=-\infty}^{\infty} \cdots \sum_{n_N=-\infty}^{\infty} J_{n_1}(2m) J_{n_2}(2m) \cdots J_{n_N}(2m) e^{j \sum_{k=1}^{N} n_k \theta_k(t)} \end{aligned} \quad \text{(B.13)}$$

Thus, the equation(B.10) is

$$i(t) = rP_{in}L_{opt}\left[1+\left[\mathrm{Re}\left[e^{j\Delta\phi}\sum_{n_1=-\infty}^{\infty}\sum_{n_2=-\infty}^{\infty}\cdots\sum_{n_N=-\infty}^{\infty}J_{n_1}(2m)J_{n_2}(2m)\cdots J_{n_N}(2m)e^{j\sum_{k=1}^{N}n_k\theta_k(t)}\right]\right]\right]$$
$$= rP_{in}L_{opt}\left[1+\mathrm{Re}\left[e^{j(\phi_1-\phi_2)}\sum_{n_1=-\infty}^{\infty}\sum_{n_2=-\infty}^{\infty}\cdots\sum_{n_N=-\infty}^{\infty}\left[J_{n_1}(2m)J_{n_2}(2m)\cdots J_{n_N}(2m)e^{j\sum_{k=1}^{N}n_k(\omega_k t+\phi_{RF1})}\right]\right]\right]$$

(B.14)

The fundamental component in h^{th} channel is;

$$n_k = \begin{cases} \pm 1 & for \quad n_h \\ otherwise & 0 \end{cases}$$

$$i_{1st}(t) = rP_{in}L_{opt}\,Re\left[e^{j(\phi_1-\phi_2)}\{J_0(2m)\}^{N-1}\left\{J_1(2m)e^{j(\omega_h t+\phi_{RF1})}+J_{-1}(2m)e^{-j(\omega_h t+\phi_{RF1})}\right\}\right]$$
$$= rP_{in}L_{opt}\,Re\left[e^{j(\phi_1-\phi_2)}\{J_0(2m)\}^{N-1}J_1(2m)\left\{e^{j(\omega_h t+\phi_{RF1})}-e^{-j(\omega_h t+\phi_{RF1})}\right\}\right]$$
$$= -2rP_{in}L_{opt}\{J_0(2m)\}^{N-1}J_1(2m)\sin(\phi_1-\phi_2)\sin(\omega_h t+\phi_{RF1})$$

(B.15)

The second harmonic component in h'th channel is;

$$n_k = \begin{cases} \pm 2 & for \quad n_h \\ otherwise & 0 \end{cases}$$

$$i_{2HD}(t) = rP_{in}L_{opt}\,\mathrm{Re}\left[e^{j(\phi_1-\phi_2)}\{J_0(2m)\}^{N-1}\left\{J_2(2m)e^{j(2\omega_h t+2\phi_{RF1})}+J_{-2}(2m)e^{-j(2\omega_h t+2\phi_{RF1})}\right\}\right]$$
$$= rP_{in}L_{opt}\,\mathrm{Re}\left[e^{j(\phi_1-\phi_2)}\{J_0(2m)\}^{N-1}J_2(2m)\left\{e^{j(2\omega_h t+2\phi_{RF1})}+e^{-j(2\omega_h t+2\phi_{RF1})}\right\}\right]$$
$$= 2rP_{in}L_{opt}\{J_0(2m)\}^{N-1}J_2(2m)\cos(\phi_1-\phi_2)\cos(2\omega_h t+2\phi_{RF1})$$

(B.16)

The third harmonic component in h'th channel is;

$$n_k = \begin{cases} \pm 3 & for \quad n_h \\ otherwise & 0 \end{cases}$$

$$i_{3HD}(t) = rP_{in}L_{opt}\,\mathrm{Re}\left[e^{j(\phi_1-\phi_2)}\{J_0(2m)\}^{N-1}\left\{J_3(2m)e^{j(3\omega_h t+3\phi_{RF1})}+J_{-3}(2m)e^{-j(3\omega_h t+3\phi_{RF1})}\right\}\right]$$
$$= rP_{in}L_{opt}\,\mathrm{Re}\left[e^{j(\phi_1-\phi_2)}\{J_0(2m)\}^{N-1}J_3(2m)\left\{e^{j(3\omega_h t+3\phi_{RF1})}-e^{-j(3\omega_h t+3\phi_{RF1})}\right\}\right]$$
$$= -2rP_{in}L_{opt}\{J_0(2m)\}^{N-1}J_3(2m)\sin(\phi_1-\phi_2)\sin(3\omega_h t+3\phi_{RF1})$$

(B.17)

Inter-modulation distortion components of the second order generated by 2-tone signals are;

$$n_k = \begin{cases} \pm 1 & for \quad n_h \\ \mp 1 & for \quad n_i \\ otherwise & 0 \end{cases}$$

$$i_{IM2}(t) = -rP_{in}L_{opt}\,\mathrm{Re}\left[e^{j(\phi_1-\phi_2)}\{J_0(2m)\}^{N-2}\{J_1(2m)\}^2\left\{e^{j(\omega_h-\omega_i)t}+e^{-j(\omega_h-\omega_i)t}\right\}\right]$$
$$= -2rP_{in}L_{opt}\{J_0(2m)\}^{N-2}\{J_1(2m)\}^2\cos(\phi_1-\phi_2)\cos\{(\omega_h-\omega_i)t\}$$

(B.18)

Inter-modulation distortion components of the third order generated by 2-tone signals are;

$$n_k = \begin{cases} \pm 2 & for \quad n_h \\ \mp 1 & for \quad n_i \\ otherwise & 0 \end{cases}$$

$$\begin{aligned} i_{IM3}(t) &= rP_{in}L_{opt}\,\mathrm{Re}\Big[e^{j(\phi_1-\phi_2)}\{J_0(2m)\}^{N-2}J_2(2m)J_{-1}(2m)e^{j\{(2\omega_h-\omega_i)t+\phi_{RF1}\}}+\{J_0(2m)\}^{N-2}J_{-2}(2m)J_1(2m)e^{-j\{(2\omega_h-\omega_i)t+\phi_{RF1}\}}\Big] \\ &= -rP_{in}L_{opt}\,\mathrm{Re}\Big[e^{j(\phi_1-\phi_2)}\{J_0(2m)\}^{N-2}J_2(2m)J_1(2m)\Big[e^{j\{(2\omega_h-\omega_i)t+\phi_{RF1}\}}-e^{-j\{(2\omega_h-\omega_i)t+\phi_{RF1}\}}\Big]\Big] \\ &= 2rP_{in}L_{opt}\{J_0(2m)\}^{N-2}J_2(2m)J_1(2m)\sin(\phi_1-\phi_2)\sin\{(2\omega_h-\omega_i)t+\phi_{RF1}\} \end{aligned} \quad \text{(B.19)}$$

Inter-modulation distortion components of the third order generated by 3-tone signals are;

$$n_k = \begin{cases} \pm 1 & for \quad n_h \quad n_i \\ \mp 1 & for \quad n_l \\ otherwise & 0 \end{cases}$$

$$\begin{aligned} i_{TB}(t) &= -rP_{in}L_{opt}\,\mathrm{Re}\left[e^{j(\phi_1-\phi_2)}\{J_0(2m)\}^{N-3}\{J_2(2m)\}^3\left\{e^{j\{(\omega_h+\omega_i-\omega_j)t+\phi_{RF1}\}}-e^{-j\{(\omega_h+\omega_i-\omega_j)t+\phi_{RF1}\}}\right\}\right] \\ &= 2rP_{in}L_{opt}\{J_0(2m)\}^{N-3}\{J_1(2m)\}^3\sin(\phi_1-\phi_2)\sin\{(\omega_h+\omega_i-\omega_l)t+\phi_{RF1}\} \end{aligned} \quad \text{(B.20)}$$

From (B.15) to (B.20), the power ratios of fundamental to distortion components are;

$$\text{2nd harmonics} = \left(\frac{\text{2nd harmonic component}}{\text{fundamental component}}\right)^2 = \left\{\frac{J_2(2m)}{J_1(2m)}\tan^{-1}(\phi_1-\phi_2)\right\}^2 \quad \text{(B.21)}$$

$$\text{3rd harmonics} = \left(\frac{\text{3rd harmonic component}}{\text{fundamental component}}\right)^2 = \left\{\frac{J_3(2m)}{J_1(2m)}\right\}^2 \quad \text{(B.22)}$$

$$\text{IM2} = \left(\frac{\text{2nd order IMD}}{\text{fundamental component}}\right)^2 = \left\{\frac{J_1(2m)}{J_0(2m)}\tan^{-1}(\phi_1-\phi_2)\right\}^2 \quad \text{(B.23)}$$

$$\text{IM3} = \left(\frac{\text{third order IMD}}{\text{fundamental component}}\right)^2 = \left\{\frac{J_2(2m)}{J_0(2m)}\right\}^2 \quad \text{(B.24)}$$

$$\text{T}riplebeat = \left(\frac{\text{triple beat component}}{\text{fundamental component}}\right)^2 = \left\{\frac{J_1(2m)}{J_0(2m)}\right\}^4 \quad \text{(B.25)}$$

Here, NOMI is defined as;

NOMI=$V_{RF}/V_{\pi RF}$×100 [%]

where V_{RF} is driving power and $V_{\pi RF}$ is half-wavelength voltage for the signal frequency.

And, the power ratio of fundamental component to distortion components are expressed as the functions of NOMI,

$$\text{2nd harmonics} = \left\{\frac{J_2\left(\frac{\pi}{2}\cdot\frac{1}{100}\cdot NOMI\right)}{J_1\left(\frac{\pi}{2}\cdot\frac{1}{100}\cdot NOMI\right)}\tan^{-1}(\phi_1-\phi_2)\right\}^2 \quad \text{(B.26)}$$

$$\text{3rd harmonics} = \left\{ \frac{J_3\left(\frac{\pi}{2} \cdot \frac{1}{100} \cdot NOMI\right)}{J_1\left(\frac{\pi}{2} \cdot \frac{1}{100} \cdot NOM\right)} \right\}^2 \qquad \text{(B.27)}$$

$$IM2 = \left\{ \frac{J_1\left(\frac{\pi}{2} \cdot \frac{1}{100} \cdot NOMI\right)}{J_0\left(\frac{\pi}{2} \cdot \frac{1}{100} \cdot NOMI\right)} \tan^{-1}(\phi_1 - \phi_2) \right\}^2 \qquad \text{(B.28)}$$

$$IM3 = \left\{ \frac{J_2\left(\frac{\pi}{2} \cdot \frac{1}{100} \cdot NOMI\right)}{J_0\left(\frac{\pi}{2} \cdot \frac{1}{100} \cdot NOMI\right)} \right\}^2 \qquad \text{(B.29)}$$

$$\text{Triplebeat} = \left\{ \frac{J_1\left(\frac{\pi}{2} \cdot \frac{1}{100} \cdot NOMI\right)}{J_0\left(\frac{\pi}{2} \cdot \frac{1}{100} \cdot NOMI\right)} \right\}^4 \qquad \text{(B.30)}$$

Therefore, IM2 and IM3 are obtained by using calculated amount of NOMI from measurement result of half-wavelength voltage.

Note in Equation B.28 that IM2 depends on the bias voltages and OMI. When the bias voltage deviates from the quadrature-point as illustrated in Figure B.2, IM2 noticeably increases as shown in Figure B.3. On the other hand, IM3 does not depend on the bias voltage, and is determined only by NOMI. The dependency of IM3 on NOMI is shown in Figure B.4

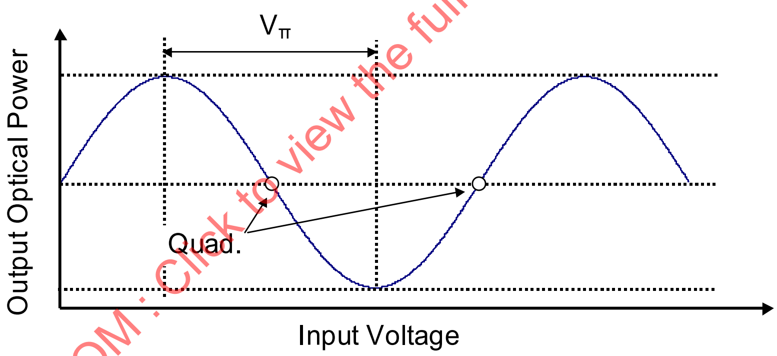

Figure B.2 – Quadrature points of a transfer cureve for a Mach-Zehnder optical modulator

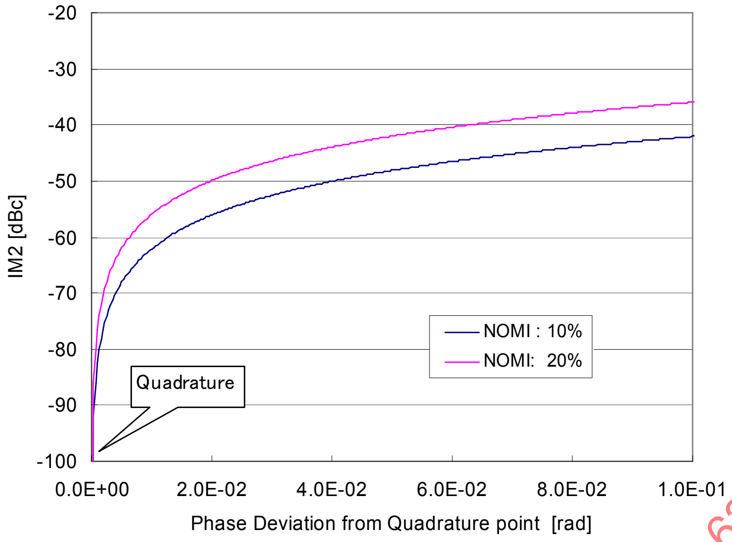

Figure B.3 – Dependency of IM2 on NOMI and Bias voltage of a Mach-Zehnder optical modulator

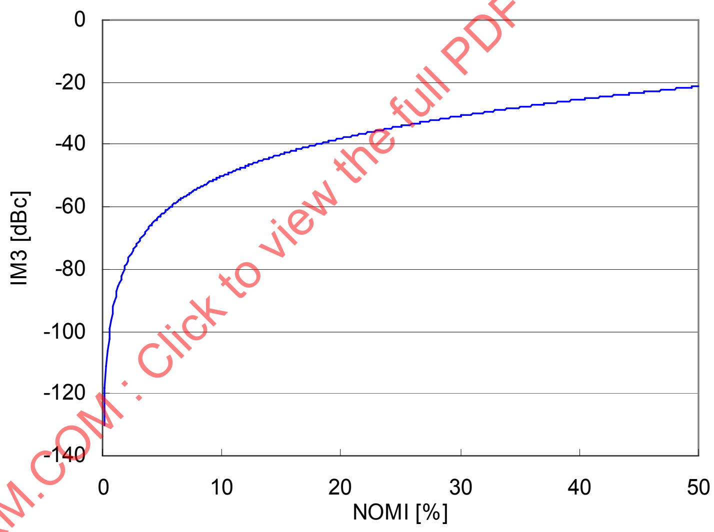

Figure B.4 – Relation between IM3 and OMI of a Mach-Zehnder optical modulator

B.3 Conventional measurement methods of intermodulation distortions

Conventional measurement methods of the second-order inter-modulation distortion (IM2) and the third-order inter-modulation distortion (IM3) of optical modulators under specified modulation conditions are described as follows

B.3.1 Circuit diagram

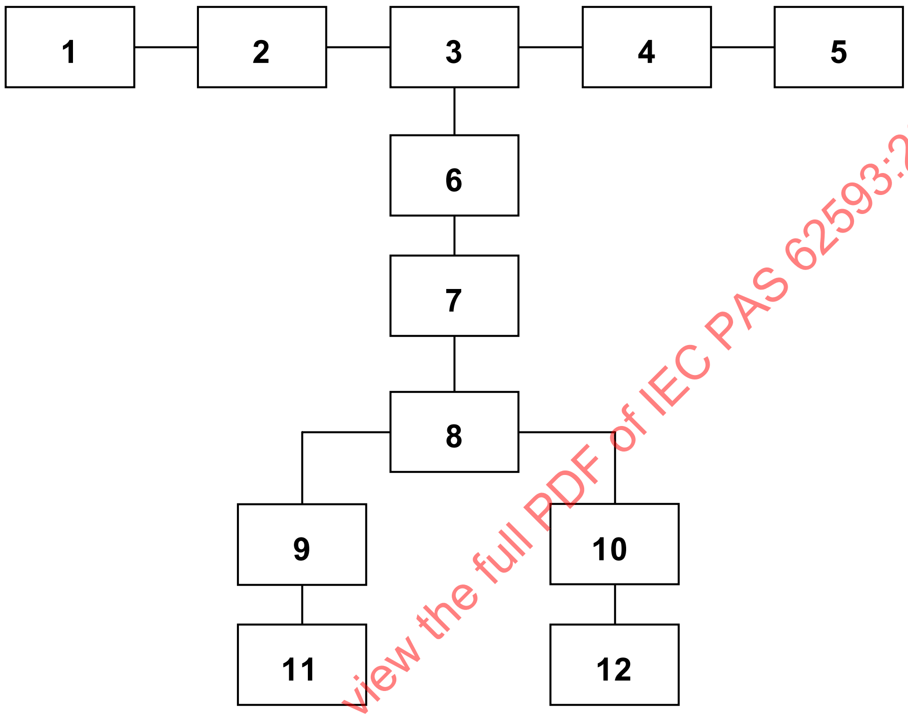

Figure B.5

Circuit description and requirement

1 = Laser diode
2 = Polarization Controller
3 = Device Under Test
4 = Photo Diode: PD
5 = Spectrum analyzer (electrical): ESA
6 = Attenuator (Electrical)
7 = Microwave Amplifier
8 = Combiner
9 = Attenuator (Electrical)
10 = Attenuator (Electrical)
11 = Microwave Signal Source (RF1)
12 = Microwave Signal Source (RF1)

B.3.2 Precaution to be observed

The modulator shall be effectively coupled to the photo diode with minimal back reflection. The input optical power to the photo diode (PD) should be kept within the line response range of PD. The electrical spectrum analyzer (ESA) should have enough dynamic range and frequency band corresponding to specified conditions.

B.3.3 Measurement procedures

Couple the optical output of the Laser diode from the specified optical port to the device under test, DUT, through the specified optical port to the photo diode (PD). Apply modulation voltage from the two sine wave sources S1 and S2 to DUT so as to create two modulation tones of signal frequency f1 and f2. The modulated optical output at the signal frequencies and the modulated optical output at the inter-modulation frequencies are recorded on ESA. Adjust S1 and S2 so that the modulated optical outputs at the signal frequencies are equal. Vary the signal attenuation with ATT1 and record the modulating power and optical signal power. Confirm the slope of IMD2(=2) and IMD3(=3) against the modulating power.

Determine the IMD2 and IMD3 by taking the ratio of the amplitude of the larger of the modulated optical inter-modulation sidebands to the amplitude of the signals.

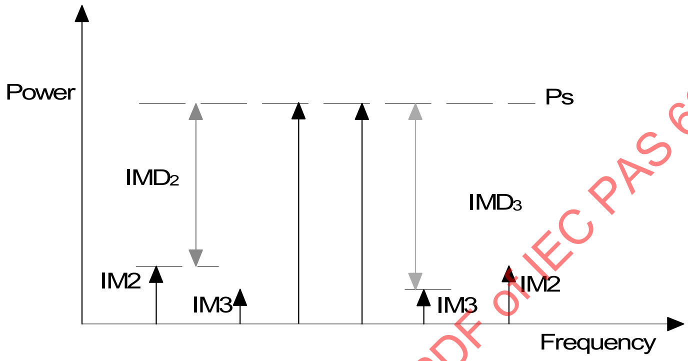

Figure B.6 – IMD2 and IMD3

Annex C
(informative)

Characteristics of a Mach-Zehnder optical modulator

C.1 Electrical and optical characteristics of a Mach-Zehnder optical modulator

Important examples of electrical and optical characteristics of a Mach-Zehnder optical modulator in wireless communication and broadcasting systems are listed in Table C.1.

The specifications for characteristics listed here are defined by agreements between users and suppliers. The specifications are expected to evolve and change as existing system requirements are refined and new applications are developed.

Table C.1

Characteristics of Optical Modulator	Letter symbol	Unit	Min	Max	Reference
Half-wavelength voltage	V_π	V	X	X	This PAS
Operating wavelength	λ	nm	X	X	
Insertion loss	L_{in}	dB		X	JIS C 6114-2
Return loss	L_{rt}	dB	X	X	
DC Extinction ratio		dB	X		JIS C 6114-2
AC Extinction ratio		dB	X		JIS C 6114-2
Polarization dependent Loss	*PDL*	dB		X	JIS C 6114-2
Polarization crosstalk	*PCT*	dB		X	JIS C 6114-2
Frequency response		MHz(GHz)		X	
Frequency response flatness		MHz/mV		X	
Wavelength chirp		MHz/mV	X	X	JIS C 6114-2
Chirp parameter (α)	α		X	X	**
Optical modulation index	*OMI*	%	X	X	IEC 62000 This PAS
Second order Intermodulation distortion	*IM2*	dBc		X	IEC 62007 series This PAS
Third order intermodulation distortion	*IM3*	dBc		X	IEC 62007 series This PAS
Composite second order distortion	*CSO*	dBc		X	IEC 62007 series
Composite third order distortion	*CTB*	dBc		X	IEC 62007 series

C.2 Mechanical and environmental characteristics

Major examples of mechanical and environmental characteristics of Mach-Zehnder optical modulator in wireless communication and broadcasting systems are listed in Table C.2.

The specifications for characteristics listed here are defined by agreements between users and suppliers. The specifications are expected to evolve and change as existing system requirements are refined and new applications are developed.

Table C.2

Characteristics of Optical Modulator	Letter symbol	Unit	Min	Max
Storage temperature	V_{π}	V	X	X
Ambient temperature	T_{amb}	°C	X	X
Soldering temperature at maximum soldering time	T_{sld}	°C		X
Bend radius of pigtail	R	mm	X	
Tensile force on fibre along its axes	F	Kg		X
Shock				X
Vibration				X

Annex D
(informative)

Points to consider for measurement

D.1 Factors of measurement uncertainty

D.1.1 Measurement equipment

a) Power Meter (Electrical):

Total Uncertainty will be within 0,2 dB and maximum power limited by +20 dBm for a normal power meter/sensor. To avoid overpower for the sensor, use a step-attenuator between DUT and the sensor. When the step attenuator is used, actual power has to be subtracted by the attenuator values.

b) Spectrum Analyzer (Electrical):

Generally, power accuracy of the Spectrum Analyzer is inferior to that of a power meter and is approximately within 2,0dB. If a Spectrum Analyzer is used, take care of its accuracy before the measurement.

Please refer to the following calculation of measurement uncertainty with medium grade spectrum analyzer.

Model: Agilent 8563EC
Frequency: 1,0 GHz
RBW: 3 kHz
ATT: 20 dB

Table D.1

Specification		(Linear-1)^2
Frequency Response	±1,0dB	0,067
Attenuator Setting	±0,6dB	0,022
Calibration Accuracy	±0,3dB	0,005
Linearity	±0,1dB	0,001
IF Gain	±1,0dB	0,067
IF BW response	±0,5dB	0,015

Total Uncertainty	{√(0,067)+(0,022)+(0,005)+(0,001)+(0,067)+(0,015)}+1	1,418
		±1,52dB

D.1.2 Measurement range

Measurement accuracy depends on power accuracy by power meter or spectrum analyzer.

A normal power meter/sensor has about ±0,2 dB total uncertainty with a -30 dBm to +20 dBm power range as shown in the following calculation of measurement uncertainty.

Test Freq:	1
Test Power (dBm):	20
DUT SWR	1,25
Sensor SWR	1,1
Sensor/source mismatch **(=ρ(sensor)×ρ(DUT)):**	0,53%
Calibrator source SWR	1,060 00
Sensor/calibrator source mismatch (=ρ(sensor)×ρ(calibrator)):	0,14%
Noise term	110
Noise multiplier	1
Zero set	50
Drift	10
	Value(±%)
Identify major source of uncertainties	
1. Source/sensor mismatch at test freq	0,53%
2. Sensor/Calibrator source mismatch at test freq	0,14%
2. Calibration factor uncertainty at test freq	1,60%
3. Linearity at test power level	3,00%
4. Power reference uncertainty	0,60%
5. Power meter Instrumentation uncertainty	0,50%
6. Power meter instrumentation uncertainty (during calibration)	0,50%
7. Measurement noise (=noise term×noise multiplier/test power)	0,000 1%
8. Zero uncertainty (=zero set/test power)	0,000 1%
9. Drift (=drift/test power)	0,000 0%
U_c (=R_{ss} of 1 to 9) =	2,01%
Expanded uncertainty (k=2) =	**4,02%**
Total Uncertainty	**0,171**
	-0,178