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INTERNATIONAL STANDARD

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Measurement methods of a half-wavelength voltage and a chirp parameter for Mach-Zehnder optical modulators in high-frequency radio on fibre (RoF) systems

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MEASUREMENT METHODS OF A HALF-WAVELENGTH VOLTAGE AND A CHIRP PARAMETER FOR MACH-ZEHNDER OPTICAL MODULATORS IN HIGH-FREQUENCY RADIO ON FIBRE (ROF) SYSTEMS

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

CDV	Report on voting
103/131/CDV	103/161/RVC

Full information on the voting for the approval of this International Standard can be found in the report on voting indicated in the above table.

This document has been drafted in accordance with the ISO/IEC Directives, Part 2.

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INTRODUCTION

A variety of microwave/millimeter-wave-photonic devices are useful for wireless communication and broadcasting systems. An optical modulator is an interface which converts an electronic signal to an optical signal. In the field of optical fibre communication systems, the IEC 62007 series was published in 1999.

Microwave/millimeter-wave RoF systems are comprised mainly of two parts: one is 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. This signal is transferred through the optical fibre and then the radio waves are regenerated at O/E.

A variety of photonic devices that carry microwave and millimeter-wave signals as subcarrier frequencies are used for high-frequency RoF systems. In particular, the Mach-Zehnder optical modulator (MZM) plays an important role to convert electronic (high-frequency above millimeter-wave) signal to optical signal. In high-frequency RoF systems, specifications of drive voltages, chirp characteristics, inter-modulation distortion of the modulators have been the important technical parameters. This document is prepared to provide the measurement method of MZMs to the industry for evaluating electro-optic material of the modulators to be used in high-frequency RoF systems. This document defines the measurement methods of a half-wavelength voltage and a chirp parameter, which have a significant impact on the performance of RoF systems. Additionally, these methods are also used for the estimation of the intermodulation distortions and transmission performances.

The half-wavelength voltage and the chirp parameter can be measured at the same time using the methods defined in this document. The nonlinear distortion characteristics are also important for the performance of the systems. The intermodulation distortion of the MZM is calculated from the driving voltage and the half-wavelength voltage. The detailed explanations and calculation method of intermodulation distortions from the normalized optical modulation index (NOMI) are described in IEC PAS 62593:2008[1][1], Annex B.

The International Electrotechnical Commission (IEC) draws attention to the fact that it is claimed that compliance with this document may involve the use of patents concerning:

a) a method for characterization of optical modulator, and method for controlling high frequency oscillator using the same (JP 3538619B),
b) a method and apparatus for measurement of characteristic of optical modulator (JP 3866082B),
c) a method for evaluating characteristic of optical modulator having Mach-Zehnder interferometer (WO 2011-027409),
d) a method of measuring half-wave voltage of optical modulator (JP 2009-229926A).

Details pertaining to the patent holders and the locations where the patents are referred to in the document are given in Table 1.

1 Numbers in square brackets refer to the Bibliography.

Table 1 – Patents present in this document

Related clause	Patent holder	Patent number
Clause 6 Annex A (informative)	National Institute of Information and Communications Technology	JP 3538619
6.4.3	National Institute of Information and Communications Technology Sumitomo Osaka Cement Co., Ltd.	JP 3866082
A.2.1	National Institute of Information and Communications Technology Sumitomo Osaka Cement Co., Ltd.	(WO 2011-027409) EP 2477021A US 8867042 CN 102575971 JP 5622154
A.2.2	Sumitomo Osaka Cement Co., Ltd.	(JP2009-229926A) JP 4991610

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MEASUREMENT METHODS OF A HALF-WAVELENGTH VOLTAGE AND A CHIRP PARAMETER FOR MACH-ZEHNDER OPTICAL MODULATORS IN HIGH-FREQUENCY RADIO ON FIBRE (ROF) SYSTEMS

1 Scope

This document specifies measurement methods of a half-wavelength voltage and a chirp parameter applicable to MZMs in microwave and millimeter-wave RoF systems. In addition, these methods are also effective for the estimation of the intermodulation distortions and transmission performances. The methods apply for the following:

– frequency range: 5 GHz to 110 GHz;

– wavelength band: 0,8 µm to 2,0 µm;

– electro-optic material based MZMs and their modules.

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.

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: Measurement methods*

3 Terms, definitions and abbreviated terms

3.1 Terms and definitions

For the purposes of this document, the terms and definitions given in IEC 62007-1:2015 and IEC 62007-2:2009 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
half-wavelength voltage
V_π
voltage required for a Pockels effect material based Mach-Zehnder optical modulator to induce a phase shift of half a wavelength between the lightwaves of two arms of the Mach-Zehnder interferometer

SEE: Figure 1.

Note 1 to entry: It corresponds to an ON/OFF voltage of the Mach-Zehnder optical modulator.

Note 2 to entry: IEC PAS 62593 defines a measurement method for a half-wavelength voltage suitable for lower frequency applications, especially less than 5 GHz.

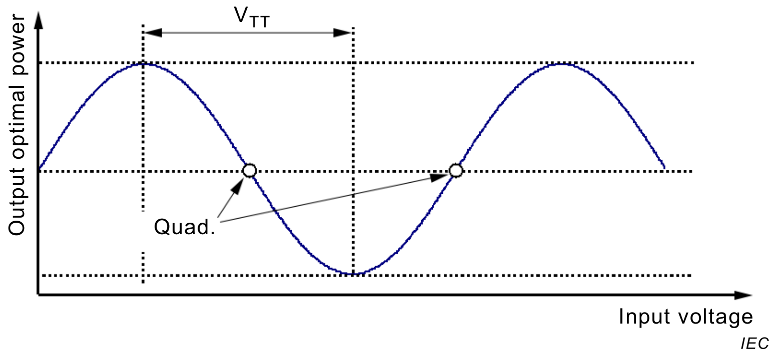


Figure 1 – Transfer curve of a Mach-Zehnder optical modulator

3.1.2
NOMI
normalized optical modulation index
for the Mach-Zehnder optical modulator, ratio of driving voltage and half-wavelength voltage of the modulator, defined as:

$$\text{NOMI} = (V_{pp} \;/\; V_{\pi}) \times 100\ [\%] \tag{1}$$

where

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

V_{π} is the half-wavelength voltage.

Note 1 to entry For the Mach-Zehnder optical modulator, the intermodulation distortion is dependent on NOMI. The detailed explanations of OMI including measurement method are described in IEC PAS 62593:2008, Annex A. The calculation method of intermodulation distortions from the measured NOMI is described in IEC PAS 62593:2008, Annex B.

3.1.3
extinction ratio
$\boldsymbol{R_{\mathrm{ext}}}$
ratio of two optical power levels of the optical signal generated by the optical modulator, defined as:

$$R_{\mathrm{ext}} = 10\log(P_1/P_2) \tag{2}$$

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 1 to entry: The extinction ratio is sometimes expressed as a fraction not in dB.

3.1.4
chirp parameter
undesired optical phase change with amplitude or intensity modulation, which is defined as the ratio of amplitude modulation and the phase modulation:

$$\alpha = \frac{d\phi}{dt} \Big/ \frac{1}{E}\frac{dE}{dt} \tag{3}$$

where

E is the optical amplitude at the modulator output,

ϕ is the optical phase at the modulator output.

Note 1 to entry: In IEC 61280-2-9 [2], chirp measurement methods for laser transmitters were overviewed, and time-resolved chirp and alpha-parameter measurement methods for of laser transmitters for digital systems is are given in IEC 61280-2-10 [3]. The chirp parameter alpha of an MZM is explained in detail in [4].

Note 2 to entry: The alpha parameter of an MZM can also be measured together with a half-wave voltage V_π by the sideband monitoring methods described in [5] and [6] using an optical spectrum analyzer.

3.2 Abbreviated terms

DC	direct current
DUT	device under test
MZM	Mach-Zehnder modulator
NOMI	normalized OMI
OMI	optical modulation index
OSA	optical spectrum analyzer
RF	radio frequency

4 Electro-optic material-based Mach-Zehnder optical modulators

4.1 Mach-Zehnder optical modulators

4.1.1 Component parts

The optical modulators and their modules consist of the 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).

4.1.2 Structure

The structure is as follows:

– electrode: lumped type, traveling-wave type, etc.
– options: optical isolator, photodiode, half-mirror, laser-diode, etc.

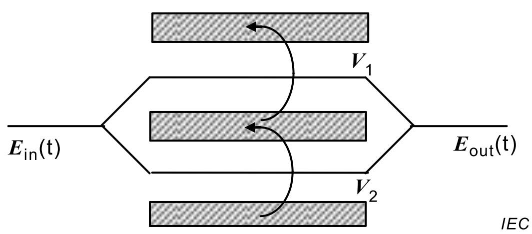


Figure 2 – Optical phase retardations

Due to the Pockels effect, optical phase retardation at each arm in the Mach-Zehnder interferometer can be controlled by the voltage applied on the electrode. The optical phase retardations at the upper arm and the lower arm are proportional to the voltages V_1 and V_2 (see Figure 2).

4.2 Requirements for MZMs

4.2.1 General

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

4.2.2 Substrate material

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

4.2.3 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 modified designs of the modulators.

5 Sampling for quality control

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

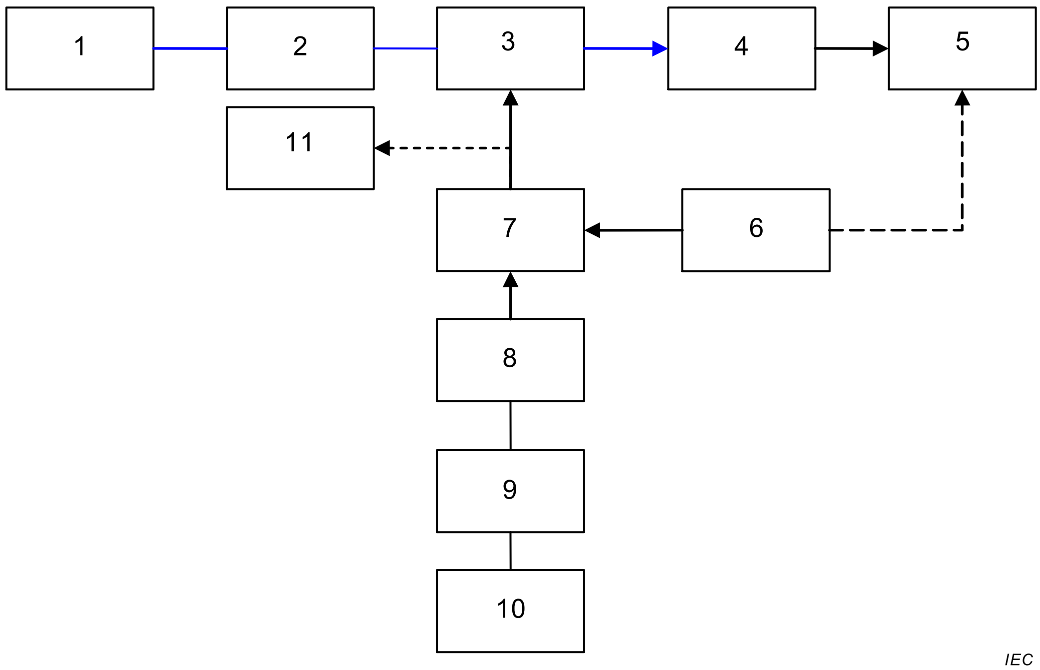
Appropriate statistical methods shall be applied to determine adequate sample size and acceptance criteria for the considered lot size. In the absence of more detailed statistical analysis, the following sampling plan can be employed:

Half-wavelength voltage: two units at least per manufacturing lot.

6 Measurement method of a half wavelength voltage

6.1 Circuit diagram

See Figure 3.



Key

The circuit description and requirements are as follows:

1 laser diode

2 polarization controller

3 device under test (DUT)

4 optical spectrum analyzer (OSA)

5 personal computer

6 DC voltage source or 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)

Figure 3 – Circuit diagram

6.2 Measurement conditions

6.2.1 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 apparatuses are narrower than this range, the specifications of the measurement apparatuses 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 apparatuses 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.

6.2.2 Warming-up of measurement equipment

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

6.3 Principle of measurement method

6.3.1 General

The method for measuring the half-wavelength voltage (RF half-wavelength voltage) of a Mach-Zehnder type optical modulator is described in 6.3. In this method, the half-wavelength voltages of Mach-Zehnder type optical modulators can be measured accurately by using an optical spectrum analyzer (OSA). When a single-tone RF signal is applied to the modulator, the optical output would have sideband components whose frequency separation is equal to the frequency of the single-tone RF signal. The induced optical phases in a MZ modulator can be calculated from the intensities of the optical sideband components measured by the OSA. When the input RF power or voltage is also measured at this condition, the half-wavelength voltage, V_π can be determined. This measurement can be achieved through a wide frequency range from a few GHz to 110 GHz, which depends on the frequency range of the RF signal generator and power meter.

6.3.2 Mathematical expressions of basic measurement principle

The optical output of an MZM is given by:

$$\begin{aligned} E &= \frac{E_i e^{j\omega_0 t}}{2}\{\exp j[A_1 \sin\omega_m t + \phi_{B1}] + \exp j[A_2 \sin\omega_m t + \phi_{B2}]\} \\ &= \frac{E_i e^{j\omega_0 t}}{2}\left\{e^{j\phi_{B1}}\sum_{n=-\infty}^{\infty} J_n(A_1)e^{jn\omega_m t} + e^{j\phi_{B2}}\sum_{n=-\infty}^{\infty} J_n(A_2)e^{jn\omega_m t}\right\} \\ &= \frac{E_i e^{j\omega_0 t} e^{j\phi_{\bar{B}}}}{2}\left\{e^{-j\phi_B/2}\sum_{n=-\infty}^{\infty} J_n(A_1)e^{jn\omega_m t} + e^{j\phi_B/2}\sum_{n=-\infty}^{\infty} J_n(A_2)e^{jn\omega_m t}\right\} \end{aligned} \tag{4}$$

$$\phi_{\bar{B}} = \frac{\phi_{B1} + \phi_{B2}}{2} \tag{5}$$

$$\phi_B = -\phi_{B1} + \phi_{B2} \tag{6}$$

where

ϕ_{B1} and ϕ_{B2} are the optical phase delays at two arms in the Mach-Zehnder interferometer in the modulator;

the phase difference ϕ_B can be controlled by DC-bias voltage applied on the electrode of the modulator;

$E_i e^{j\omega_0 t}$ is the electric field of the input lightwave, where ω_0 is the angular frequency of the input lightwave and ω_m is that of the RF signal;

A_1 and A_2 are the optical phase retardation due to the RF signal fed to the electrode in the modulator.

J_n is the first kind Bessel's function. Intensities of sideband components, which correspond to the n-th order terms in Equation (4), can be measured by using an OSA. Nonlinear simultaneous equations for A_1 and A_2 can therefore be obtained.

The half-wavelength voltage V_π was derived from A_1 and A_2 using:

$$V_\pi = \frac{\pi V_{pp}}{2(A_1 - A_2)} \tag{7}$$

If the case of a small amplitude modulation where A_1 and A_2 < 1 is considered, the chirp parameter, the ratio of the amplitude modulation and the phase modulation can be described by:

$$\alpha_0 = \frac{A_1 + A_2}{A_1 - A_2}, \tag{8}$$

where the DC-bias is $|\phi_B| = \pi/2$, which corresponds to an optimal condition for small amplitude modulation [6]. A_1 and A_2 have opposite polarity in properly designed MZMs using push-pull configuration which provides effective intensity modulation. If the modulator has a symmetric structure with respect to the optical waveguide, A_1 equals $-A_2$, so that α_0 equals 0, which corresponds to a zero-chirp modulator. Assuming that nonlinear optical effects, except the Pockels effect, are negligible, the ratio between A_1 and A_2 does not depend on the intensity of the electric signal. Thus, α_0 is also an intrinsic parameter of the modulator. There are various options in the selection of the simultaneous equations.

6.3.3 Principle of half-wavelength voltage and chirp parameter with fixed DC-bias condition (method A)

The ratio between the n-th and (n+1)-th order sideband intensities in the optical spectrum is expressed by:

$$\begin{aligned} R_n &= \frac{\left|J_n(A_1) + J_n(A_2)e^{j\phi_B}\right|^2}{\left|J_{n+1}(A_1) + J_{n+1}(A_2)e^{j\phi_B}\right|^2} \\ &= \frac{\{J_n(A_1)\}^2 + \{J_n(A_2)\}^2 + 2J_n(A_1)J_n(A_2)\cos\phi_B}{\{J_{n+1}(A_1)\}^2 + \{J_{n+1}(A_2)\}^2 + 2J_{n+1}(A_1)J_{n+1}(A_2)\cos\phi_B} \end{aligned} \tag{9}$$

If the electrode is not DC-coupled, the phase difference ϕ_B can not be controlled by the bias voltage. Simultaneous equations for ϕ_B, A_1 and A_2 therefore need to be solved. For example, by using three equations, R_0, R_1, *and* R_2, ϕ_B, A_1 and A_2 can be obtained. When ϕ_B can be precisely controlled, A_1 and A_2 can be determined from two R_n*'s*. The number of equations is equal to that of unknown variables, but these equations are transcendental. Thus, several solutions may be derived, and some of them may be unphysical. Actual solutions can be obtained by using more equations than the number of unknown variables.

6.3.4 Principle of half-wavelength voltage and chirp parameter using DC-bias sweep (method B)

Factor $\cos\phi_B$ in Equation (9) shows the connection between the optical spectrum and the DC-bias voltage. ϕ_B depends on the environmental conditions, which is known as DC-drift. Because the half-wavelength voltage V_π does not change much, the effect of DC-drift can be eliminated by sweeping the DC-bias voltage across two times V_π for DC, which corresponds to a period of $\cos\phi_B$. The ratio of the optical sideband intensities is expressed by:

$$R_n = \frac{\{J_n(A_1)\}^2 + \{J_n(A_2)\}^2}{\{J_{n+1}(A_1)\}^2 + \{J_{n+1}(A_2)\}^2} \tag{10}$$

and does not depend on the DC-bias voltage, so A_1 and A_2 can be precisely determined.

6.3.5 Principle of half-wavelength voltage and chirp parameter using minimum transmission bias and maximum transmission bias (method C)

If ϕ_B can be precisely controlled, A_1 and A_2 can be obtained from the zeroth and first order sideband components, where two types of DC-bias conditions are used. The intensity of the n-th order sideband can be expressed by:

$$P_n = E_i^2 \frac{\left|J_n(A_1) + J_n(A_2)e^{j\phi_B}\right|^2}{4} = E_i^2 \frac{\{J_n(A_1)\}^2 + \{J_n(A_2)\}^2 + 2J_n(A_1)J_n(A_2)\cos\phi_B}{4} \quad (11)$$

When no RF signal is applied to the modulator, A_1 and A_2 are equal to zero. The optical power is given by:

$$P_0' = E_i^2 \frac{1+\cos\phi_B}{2} \quad (12)$$

P_0' depends on the DC-bias and E_i^2 shows the peak power of the optical output without RF signal input. Two DC-bias points are used: the maximum transmission bias $\phi_B = 0$ ($P_0' = E_i^2$), and the minimum transmission bias $\phi_B = \pi$ ($P_0' = 0$). At the maximum transmission bias, P_0 has the maximum (P_{oa}), while P_1 has the minimum. At the minimum transmission bias, P_1 has the maximum (P_{1b}), while P_0 has the minimum. P_0 can therefore be accurately measured at the maximum transmission bias, and P_0 at the minimum transmission bias, because the other spectral components are much smaller than the desired component. P_{oa} and P_{1b} are normalized by E_i^2, and expressed by:

$$P_{0a} / E_i^2 = \frac{\{J_0(A_1)\}^2 + \{J_0(A_2)\}^2 + 2J_0(A_1)J_0(A_2)\cos\phi_B}{4} \quad (13)$$

$$P_{1b} / E_i^2 = \frac{\{J_1(A_1)\}^2 + \{J_1(A_2)\}^2 - 2J_1(A_1)J_1(A_2)\cos\phi_B}{4} \quad (14)$$

P_{oa} and P_{1b} are normalized by E_i^2 and can be measured by an OSA or an optical power meter. A_1 and A_2 are determined from Equations (13) and (14).

6.4 Measurement procedure

6.4.1 Method A

The measurement procedure for Method A is as follows:

1) The measurement setup is prepared as shown in Figure 3.
2) The output signal of SG1 is set as follows:

   Frequency: measurement frequency of driving voltage (10 GHz, 26 GHz, etc.)

   Output power: >0 dBm at the RF input port of the modulator.
3) Intensities of optical sideband components (0th, 1st, 2nd, 3rd and 4th) are measured by using an OSA.

4) ϕ_B, A_1 and A_2 are numerically calculated from three simultaneous equations from R_0, R_1, R_2 and R_3 (see Equation (9)). To confirm the validity of the solution, ϕ_B, A_1 and A_2 are put to the Equation (9) which is not used to calculate them.

5) The half-wavelength voltage V_π and the chirp parameter α_0 are obtained from A_1 and A_2 by using $V\pi = \frac{\pi V_{pp}}{2(A_1 - A_2)}$ and $\alpha_0 = \frac{A_1 + A_2}{A_1 - A_2}$.

6.4.2 Method B

The measurement procedure for Method B is as follows:

1) The measurement setup is prepared as shown in Figure 3.
2) The output signal of SG1 is set as follows:

   Frequency: measurement frequency of driving voltage (10 GHz, 26 GHz, etc.)

   Output power: >0 dBm at the RF input port of the modulator.
3) V_π at d.c. is measured.
4) The output signal of SG2 is set as follows:

   Frequency: low frequency (1 kHz, 100 kHz, etc.)

   Output amplitude: 2 V_π at d.c.
5) Intensities of optical sideband components (0th, 1st, 2nd and 3rd) are measured by using an OSA.
6) A_1 and A_2 are numerically calculated from two simultaneous equations from R_0, R_1, and R_2 (see Equation (10)). To confirm the validity of the solution, A_1 and A_2 are put into Equation (10), which is not used to calculate them.
7) The half-wavelength voltage V_π and the chirp parameter α_0 are obtained from A_1 and A_2 by using $V\pi = \frac{\pi V_{pp}}{2(A_1 - A_2)}$ and $\alpha_0 = \frac{A_1 + A_2}{A_1 - A_2}$.

6.4.3 Method C

The measurement procedure for Method C is as follows:

1) The measurement setup is prepared as shown in Figure 3.
2) The bias voltage is set as follows:

   The intensity of optical output power becomes the maximum value.
3) The optical output power without RF input signal (P_0) is measured.
4) The output signal of SG1 is set as follows:

   Frequency: measurement frequency of driving voltage (10 GHz, 26 GHz, etc.)
5) The bias voltage is readjusted as follows:

   The intensity of the optical carrier (optical side band 0th) becomes the maximum value.
6) The intensity of the optical carrier P_{0a} is measured by using an OSA.
7) The bias voltage is set as follows:

   The intensity of the optical carrier (optical side band 0th) becomes minimum.
8) The intensity of the 1st optical sideband P_{1b} is measured by using an OSA.

9) P_{oa} and P_{1b} are normalized by E_i^2 (= P_0). A_1 and A_2 are numerically calculated from the two simultaneous equations, Equations (10) and (11).

10) The half-wavelength voltage V_π and the chirp parameter α_0 are obtained from A_1 and A_2 using $V\pi = \frac{\pi V_{pp}}{2(A_1 - A_2)}$ and $\alpha_0 = \frac{A_1 + A_2}{A_1 - A_2}$.

Annex A
(informative)

Measurement methods for parallel integrated Mach-Zehnder modulators

A.1 General

The methods described in this document are applicable to integrated MZMs. By using a parallel integrated MZM consisting of plural sub-MZMs, vector modulation and multilevel modulation can be generated and, therefore, the quadrature phase-shift-keying (QPSK) using a dual parallel modulator is prevailing technology. More integrated MZMs, such as quad-parallel MZMs, octet-parallel MZMs, which can synthesize optical multi-level signals from binary data stream generated by electronics designed for binary modulation formats, have been developed. Measurement of modulator characteristics are very important in order to achieve precise and high-speed optical modulation. However, the parallel MZMs have many electrodes to control, so that precise characterization of MZMs is not easy.

Annex A gives examples of measurement for parallel integrated MZMs. Precise measurement of half-wave voltage, extinction ratio and chirp parameter of each MZM element can be achieved using an optical spectrum analysis [1,3]. Method A is particularly suitable for the measurement of integrated modulators.

A.2 Examples

A.2.1 Quad parallel Mach-Zehnder modulators

In a quad parallel MZM (QP-MZM) consisting of quad sub MZM elements, seven-dimensional bias control is needed for the operation. However, characteristics of one of the MZM elements can be measured without turning off the other elements, using Method A or Method B, in which driving voltage and chirp parameter can be obtained without measurements of intensities of optical carrier component [1,3].

An electric sinusoidal signal is fed to one of the MZM elements, as shown in Figure A.1. When the electric isolation between the electrodes is high enough, the first and higher order sideband components are generated only at the sub-MZM element to which the electric signal is applied, while the zeroth-order (carrier) component is composed of lightwaves from all MZM components. The characterization of a particular sub-MZM element can be achieved by using the first and higher order sideband components using method A.

On the other hand, as bias control is needed, method C is used to achieve precise characterization of sub-MZMs. For the measurement of the first MZM element of a QP-MZM, optical phase differences in the second, third and fourth elements should be π to turn off other elements other than the first, where sideband components including the zeroth-order would be used to obtain a half-wave voltage and a chirp parameter.

Examples of measured results are as follows:

Half-wave voltages and intrinsic chirp parameters of four MZM elements in a QP-MZM monolithically integrated on a lithium niobate substrate were measured. The 3-dB bandwidth of the E/O response measured by a lightwave component analyzer (Agilent, 86030A) with a 1 548 nm wavelength light source was 16 GHz. A 10-GHz sinusoidal signal was applied on one of the MZM elements. Intensities of the first, second and third optical sidebands were measured by an optical spectrum analyzer. The ratio between the first, second, third and fourth order sideband intensities in the optical spectrum of each sub-MZM (MZM_1 MZM_2, MZM_3 and MZM_4) at 10 GHz were measured. Half-wave voltages and chirp parameters were derived from simultaneous transcendental equations described in 6.3.3. The number of unknown variables is equal to the number of equations to be solved in general. However, the equation would have several solutions because these equations are nonlinear. In this case, more than three equations were used to select consistent solutions. Half-wave voltages of MZM elements derived from R_n's in a 1 525 nm to 1 575 nm wavelength region are shown in Figure A.2, where the difference in the half-wave voltages of the MZM elements was less than 6 %. The chirp parameters of MZM elements are shown in Figure A.3. The chirp parameters were less than 0,1 for all the elements.

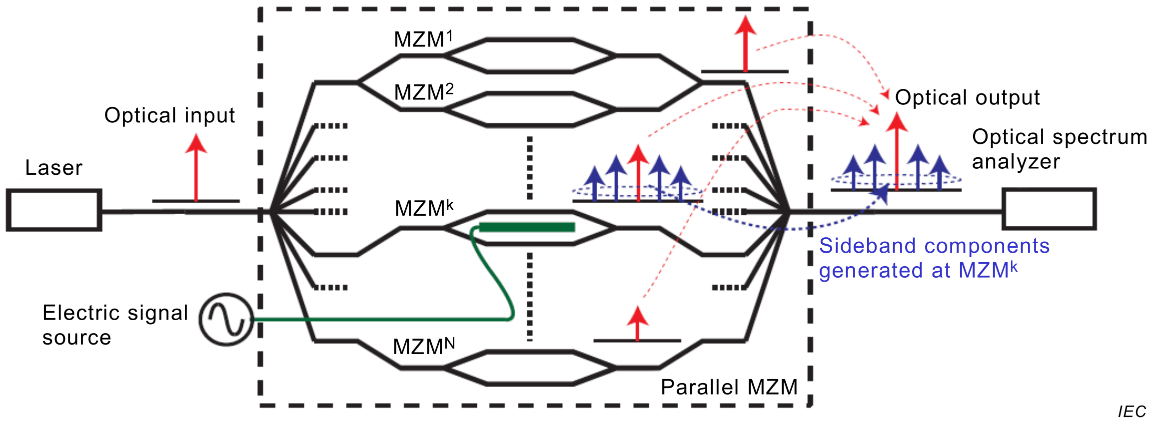


Figure A.1 – Optical sideband generation from a sub-MZM element in a parallel MZM

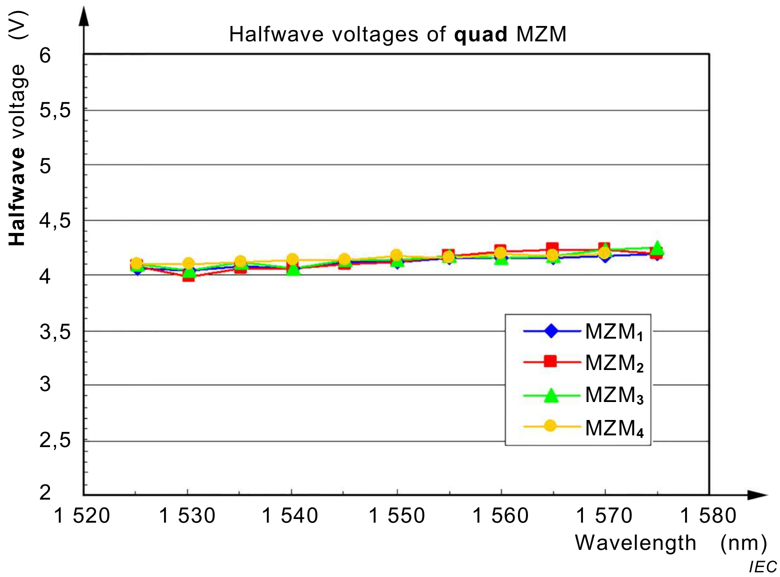


Figure A.2 – Halfwave voltages of sub-MZMs of a quad parallel MZM

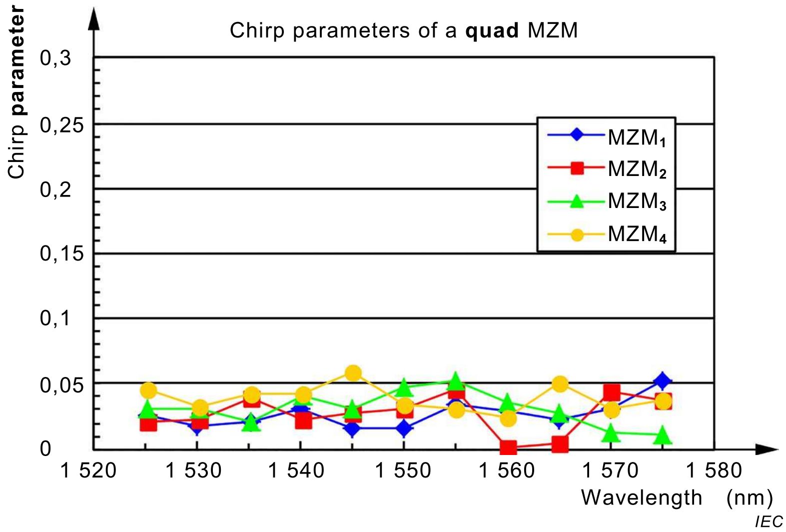


Figure A.3 – Chirp parameters of sub-MZMs of a quad parallel MZM

A.2.2 Dual parallel Mach-Zehnder modulators with four RF electrodes

For the chirp parameter control and the reduction of drive voltage, push-pull operations using dual-electrodes MZMs biased at quadrature point have been used. Dual parallel Mach-Zehnder modulators (DP-MZMs) composed of two sets of dual electrodes sub-MZMs as shown in Figure A.4 have also been provided and used widely. The sub-MZM A and B are dual electrodes type MZMs and each electrode A1, A2, B1 and B2 modulates the phase of lightwave at each arm. In this configuration, a chirp parameter of a sub-MZM can be controlled by adjusting the voltage of the signal to each phase modulator.

When electric isolation between the electrodes is high enough, the first and higher order sideband components are generated only at the phase modulator element to which the electric signal is applied, while the zeroth-order (carrier) component is composed of lightwaves from all MZM components. The measurement of half-wave voltage of a particular phase modulator element can be achieved easily by using the first and higher order sideband components without turning off the other elements [4].

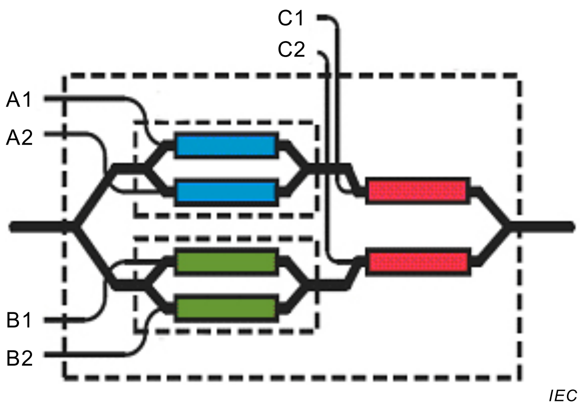


Figure A.4 – Structure of dual parallel Mach-Zehnder modulators with four RF electrodes

For phase modulators using the Pockels effect only, carrier and sideband components of the modulated lightwave spectrum are expressed by:

$$Ae^{j\omega_0 t}e^{j\pi\frac{V_{pp}}{2V_\pi}\sin(\omega_m t)} = Ae^{j\omega_0 t}\sum J_n\left(\pi\frac{V_{pp}}{2V_\pi}\right)e^{jn\omega_m t} \quad \text{(A.1)}$$

where

A is a constant which corresponds to optical power of input light,

ω_o is the angular frequency of the input lightwave and ω_m is that of the RF signal,

V_{pp} is the voltage of input RF signal,

V_π is the half-wave voltage.

The $V\pi$ in Equation (A.1) is the voltage required for inducing a phase change of one-half a wavelength of the lightwave at the phase modulator to which the electrical signal is applied. J_n is the first kind Bessel's function. Intensities of sideband components, which correspond to the n-th order terms in Equation (A.1), can be measured by using an OSA.

The ratio of side band peak intensity P_1 and P_2 is therefore given by:

$$P_1 - P_2[dB] = 10\log\left[J_1\left(\pi\frac{V_{pp}}{2V_\pi}\right)\right]^2 - 10\log\left[J_2\left(\pi\frac{V_{pp}}{2V_\pi}\right)\right]^2 \quad \text{(A.2)}$$

The half-wavelength voltage V_π of the phase modulator element is obtained from the measurement result of applied voltage V_{pp} and intensities of side band peaks P_1 and P_2 using Equation (A.2) without adjusting bias conditions [4].

An example of the measurement procedure is as follows.

1) The measurement setup is prepared as shown in Figure 3.
2) The output signal of SG1 is set as follows:
   Frequency: measurement frequency of driving voltage (10 GHz, 26 GHz, etc.)
   Output power: > 0 dBm at the RF input port of the modulator.
3) Intensities of optical sideband components (1st, 2nd) are measured using an OSA.
4) The half-wavelength voltage V_π is obtained from Equation (A.2).

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