Integrated optical RF intensity modulators transfer function traits

V S Gerasimenko, N D Gerasimenko and V M Petrov
ITMO University, Kronverkskiy 49, St. Petersburg, 197101, Russia
lyagacruz@gmail.com

Abstract. The most common integrated optical intensity modulators are made according to the Mach-Zehnder interferometer scheme. It leads to specific interconnection between the interferometer arms phase difference and the output spectrum. The description and the experimental demonstration of this traits are presented.

1. Introduction
Nowadays, LiNbO3 is one of the most common platforms for optical modulators manufacturing. That material has a strong linear electro-optic effect, which is suitable for phase modulation. At the same time lithium niobate is transparent in all optical fiber telecommunication bands. As a result, the intensity modulator on LiNbO3 uses Mach-Zehnder interferometer architecture. While it’s hard to guarantee stability of phase difference in two arms, an active tuning can be used to adjust proper values. This process is called bias point or q-point (QP) stabilization.

2. Specific points of IM transfer function
All the commercial lithium-niobate Mach-Zehnder IM uses about the same architecture: the optical part consist of two waveguides, that are connected in both sides by 3 dB Y-directional couplers, and three traveling wave electrodes are mounted on top of the optical part [1]. The signal source is connected to the central electrode, so electric field affects both waveguides symmetrically (Fig.1).

As IM uses interference, output intensity changes according to harmonic function. It leads us to mark two types of specific QPs: the first ones are points right between transfer function extrema, which is center of this function linear part, and the second ones are extrema themselves.

While QP is set to the center of the transfer function linear part and a control voltage is small enough, the IM response to the electrical signal is linear, so this operating mode is called the linear mode. In the normal linear mode, only first order subcarriers appear in the output spectrum (Fig. 2, a). However, if the control voltage is increased enough, there would appear a small additional intensity change on a triple signal frequency during the passage of the extrema (Fig. 2, b). Thus, for the QP in a linear mode, only odd number harmonics would be generated for any control voltage.
For the QP in the extrema, an output intensity changes symmetrically for both control voltage signs, so even a small amplitudes lead to the second order harmonic generation without appearance of the first one (Fig. 2, c). As in linear mode, passage of the extrema adds spectral peaks, that stay in doubled control frequency behind the previously generated ones (Fig. 2, d). It means that the mode with QP in extremum leads to only even harmonics orders generation.

**Figure 1.** The scheme of integrated optical IM on LiNbO$_3$ substrate. Electrodes, optical waveguides and electrical fields are shown. 1 – traveling wave electrodes, 2 – DC electrodes (bias control), 3 – polarizer for input light. (a) General view, (b) crosscut. [2]

**Figure 2.** Nonlinearities of IM. QP — transfer function bias point, L — linear part of the transfer function, $v(t)$ — control voltage, $i(t)$ — output intensity (measured by photodiode), $t$ – time. (a) linear mode, (b) odd harmonics generation at a large control signal amplitude with q-point is set to linear part of transfer function, (c) q-point is set to one of the transfer function extremum, nonlinear mode, second harmonics generation, (d) even harmonics generation at a large control signal amplitude with q-point is set to extremum of transfer function.
3. Mathematical description

The IM output signal on photodiode can be described as:

\[ i(t) = \frac{I(t)S}{2} \left(1 - \cos \left(\frac{QP + \pi V}{V_{\pi}}v(t)\right)\right), \]  

(1)

where \( i(t) \) – output signal, \( I(t) \) – input light intensity, \( S \) – photodiode sensitivity, \( QP \) – bias point value, \( V_{\pi} \) – halfwave voltage, and \( v(t) \) – control voltage.

We use a sine function to model simple control signal:

\[ v(t) = v \sin(\omega t), \]  

(2)

where \( v \) – control voltage amplitude, \( \omega \) – its frequency, \( t \) – time.

After combination of formulas (1) and (2) the cosine could be expanded as a row:

\[ \cos \left(\frac{QP + \pi V}{V_{\pi}}v \sin(\omega t)\right) = \Re \left\{ \exp(iQP) \sum_{n} \frac{\pi v}{V_{\pi}} J_n \left(\frac{\pi V}{V_{\pi}}\right) \exp(\imath n \omega t) \right\} = i, \]  

(3)

where \( J_m \) is the \( m \)th order Bessel function of the 1st kind and \( n = 0, \pm 1, \pm 2 \ldots \)

Formula (4) demonstrates, that the value of \( QP \) is the main element of harmonics suppression and intensification. For \( PQ = \pm \frac{\pi}{2} + \pi \mathbb{Z} \) even harmonics orders are completely suppressed, while for \( PQ = \pi \mathbb{Z} \) odd ones generation stops.

4. Experiment

The mathematical description presented above gives us understanding of an ideal QP setting. However, in real systems external factors slowly changes interferometer arms phase difference, and we must have the criterion for bias adjustment accuracy. There is a formula to find a QP setting error at which the 2nd order harmonic became equal to 3rd one at the shot noise level for the linear mode of IM working [3]:

\[ \epsilon = QP - \frac{\pi}{2} = -\frac{1}{3^{2/3} \left\{ \frac{i_{avg}}{qB} \right\}^{1/6}}, \]  

(4)

where \( \epsilon \) – QP setting error, \( q \) – electron charge, \( B \) – photodiode frequency band, and \( i_{avg} \) – average photocurrent of shot noise.

As a reference, we use values of \( i_{avg} = 1 \, mA \) and \( B = 1 \, Hz \) and find, that QP must be set with error less than \( \epsilon = 0.0015 \, radians \). For experimental purposes the voltage is more suitable, and common \( V_{\pi} = 5-7 \, V \), so QP must be set with accuracy about 0.007-0.010 \, V. It’s hard to do it on configurable voltage source by hands, because ‘slow’ effect of external factors changes proper bias value even in time about 1 second. Thus, in general an automatic tuning system must be used. At the same time, it’s possible to demonstrate, that even with inaccurate manual adjustment odd or even harmonics can be suppressed (Fig. 3). The laser source, used for experiment, has a wavelength of 1550 nm, spectral line of less than 1 MHz, and the output power of 2 mW. The IM of our production was used [2].
5. Results and discussion
It was shown, that the orders of the generated harmonics depends on the bias settings of the intensity modulator. If QP is adjusted to the center of a linear part of transfer function, only odd orders would appear. However, only even harmonics are generated, while QP is tuned to a transfer function extremum. Even more, it was shown, that the errors of QP settings must be less than 0,1% to show the effect the most impressive way. Both harmonics kinds appeared for any other QP settings, but they are related as sine and cosine.

The described effect allows us to use spectral sensitive detection methods to increase single channel information capacity by encoding additional information in a frequency choice. Alternatively, we can use frequency itself as main information carrier (it does not work for quantum channels though). As an other way, we can implement the effect in a network with spectral demultiplexion for instant change of used channel.

References
[1] Petrov V, Shamrai A Interference and Diffraction for Information Photonics. – SPb.: Lan’. 2019. 460 pp.
[2] Petrov V, Shamrai A et al. 2020 Photonics Russia 14.5 414–23
[3] Kolner B and Dolfi D 1987 Applied Optics 26.17 3676-80.