

# Bias driver of the Mach-Zehnder intensity electro-optic modulator, based on harmonic analysis

J. Svarny

**Abstract**—An adjustment of operating point significantly affects performance of the analog intensity modulator of Mach-Zehnder type. Especially, the harmonic distortion figure induced by the modulator itself must be kept at minimum by the set-up. The requirement is vital for a successful optical link design. The paper deals with design and implementation of a specialized circuit - the bias driver for extremely precise and swift retrieval of desired operating point of the modulator. The bias driver works on principle of suppression of second harmonic component detected at the modulator output while the modulator is excited with a low-frequency harmonic signal.

**Keywords**—Electro-optic modulation, bias driver, Mach-Zehnder modulator, modulator drift, harmonic analysis

## I. INTRODUCTION

THE integrated intensity Mach-Zehnder modulator (MZM) represents a powerful mean of external modulation of optical signal. By the MZM an intensity of steady laser beam can be modulated from DC up to GHz range. The device can be described as a two-arm interferometer integrated in LiNbO<sub>3</sub> substrate. It consists of two waveguides linked together with input and output optical Y junctions. The system of electrodes is positioned in tight proximity to the waveguides and arranged in an appropriate configuration to ensure effective generation of electrical field in waveguides region.

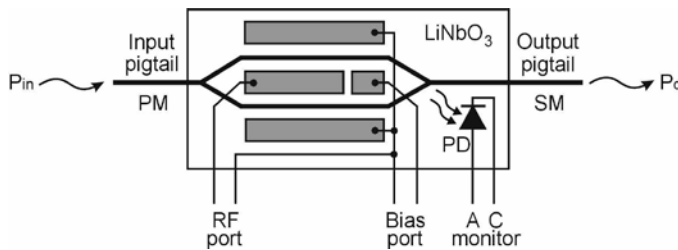


Fig.1 Configuration of integrated intensity MZM

This research has been supported by the European Regional Development Fund and the Ministry of Education, Youth and Sports of the Czech Republic under the Regional Innovation Centre for Electrical Engineering (RICE), project No. CZ.1.05/2.1.00/03.0094.

J. Svarny is with the Department of Technologies and Measurements, Faculty of Electrical Engineering / RICE, University of West Bohemia, Pilsen, Czech Republic (phone: +420-377-634-559; fax: +420-377-634-502; e-mail: svarny@ket.zcu.cz).

Commercially available modulators are usually equipped with separated radiofrequency (RF) port and bias port (Fig.1). The RF port works as balanced "π" input for broadband modulating signal. The bias port serves as an input of driving voltage for the desired operating point set-up.

A voltage applied to the electrical input (either the bias one or the modulating one) modifies the refractive index of the LiNbO<sub>3</sub> substrate. It leads to the phase shift between the light waves moving through the particular waveguides. A zero phase shift between the waves yields constructive recombination and thus maximum intensity at the output pigtail. In case the phase opposition is induced, the recombination is destructive. Minimum of radiation leaves the modulator output pigtail then. Gradual transition between these two extremes allows smooth change of output optical power. Considering excitation of only one electrical port of the MZM at the time (the bias port for instance), the idealized transfer chart can be described by cosine function (1).

$$P_o = \frac{P_{in}\alpha}{2} \left[ 1 + \cos\left(\frac{V_{in}}{V_{\pi}} \pi\right) \right], \quad (1)$$

where P<sub>o</sub> and P<sub>in</sub> is output and input optical power respectively, V<sub>in</sub> is input voltage of bias port, V<sub>π</sub> is half-wave voltage of bias port and α is insertion loss of the modulator. The corresponding transfer chart is depicted by black curve in Fig.2.

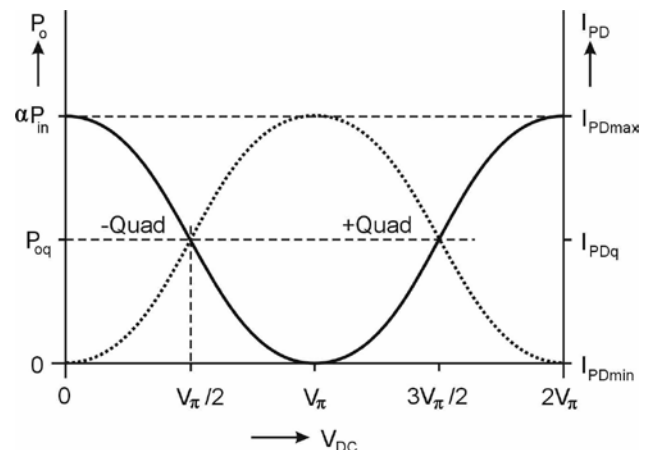


Fig.2 MZM transfer chart and inner PD chart

Some manufacturers equip their modulators with auxiliary - in the substrate buried photodiode (PD). The PD is positioned just behind the output Y junction. Advantageously, the PD signal can be used to monitor the modulator output excluding necessity to use an external tap-coupler. In case of the PowerLog™ FA20 type modulator (Fig.3) by Avanex Inc. [1] that has been used in the presented application the PD works in radiating mode. That means the PD current (dotted curve in Fig.2) is inversely proportional to the output optical power.



Fig.3 PowerLog™ FA20 analog intensity modulator

## II. THE ISSUE SPECIFICATION

One of the major problems linked with practical application of Mach-Zehnder intensity modulators is drift of the operating point. It is caused by pyro-electric, photorefractive and photoconductive phenomena that take action simultaneously in the LiNbO<sub>3</sub> substrate. The movement of the transfer charts due to the drift (gray curves in Fig.4) produces bias error and cause the modulator performance deterioration. That is why the operating point can not be fixed by steady set-up. To achieve desired performance of the device the operating point set-up must be adjustable and well controlled.

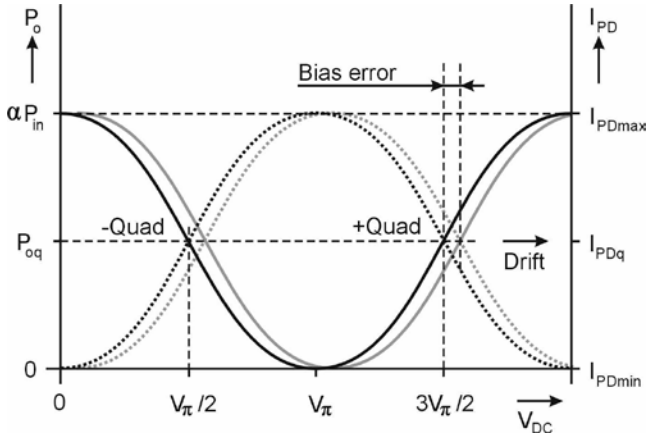


Fig.4 Bias error arise due to the drift

In case of long-period working systems the operating point is preferably stabilized with some kind of automatic feedback controller. There are lots of various techniques to control the operating point [2], [3]. Unfortunately, all the automatic feedback control techniques bring some drawbacks and limitations. Usually, the operating point is stabilized on expense of disturbance of transmitted signal. The stabilization precision and level of disturbance induced by an auxiliary signal or signals have to be well balanced and are subjects of compromise then. On the other hand, in case of short-period

working analog optical links (i.e. when the measurement or transmission process is expected to be finished within several minutes after the set-up), the initial set-up precision seems to be more important. The automatic feedback control is not necessary then. Alternatively, it can be substituted by a from time to time manual adjustment [4]. Nevertheless, the MZM operating point adjustment must be adequately swift, effective and precise.

## III. METHOD

In analog optical links the harmonic distortion figure is the major criterion for the design evaluation. Naturally, the lowest possible harmonic distortion of the link is usually desired. The modulator operating point should be set in accordance with this requirement.

Let us suppose the modulator excited by the bias port only. Simultaneously, the RF port is left open. Provided the input bias voltage is formed by DC component  $V_{DC}$  and superposed AC harmonic component with  $V_{AC}$  amplitude (2), the equation (1) can be rewritten to form (3).

$$V_{in} = V_{DC} + V_{AC} \sin(\omega_{AC}t), \quad (2)$$

$$\begin{aligned} P_o &= \frac{\alpha P_{in}}{2} \left\{ 1 + \cos \left[ \frac{V_{DC}}{V_\pi} \pi + \frac{V_{AC}}{V_\pi} \pi \sin(\omega_{AC}t) \right] \right\} = \\ &= \frac{\alpha P_{in}}{2} + \frac{\alpha P_{in}}{2} \cos \left( \frac{V_{DC}}{V_\pi} \pi \right) \cos \left[ \frac{V_{AC}}{V_\pi} \pi \sin(\omega_{AC}t) \right] - \\ &\quad - \frac{\alpha P_{in}}{2} \sin \left( \frac{V_{DC}}{V_\pi} \pi \right) \sin \left[ \frac{V_{AC}}{V_\pi} \pi \sin(\omega_{AC}t) \right], \quad (3) \end{aligned}$$

The equation (3) can be rearranged by means of formulas (4) and (5).

$$\cos(x \sin y) = J_0(x) + 2 \sum_{k=1}^{\infty} J_{2k}(x) \cos(2ky), \quad (4)$$

$$\sin(x \sin y) = 2 \sum_{k=1}^{\infty} J_{2k-1}(x) \sin[(2k-1)y], \quad (5)$$

where  $J_k(x)$  is a  $k^{\text{th}}$  order Bessel function. Using the Bessel functions the output optical power (3) can be rewritten to reveal particular harmonics (6).

$$\begin{aligned} P_o &= \frac{\alpha P_{in}}{2} + \frac{\alpha P_{in}}{2} \cos \left( \frac{V_{DC}}{V_\pi} \pi \right) J_0 \left( \frac{V_{AC}}{V_\pi} \pi \right) + \\ &+ \alpha P_{in} \cos \left( \frac{V_{DC}}{V_\pi} \pi \right) \sum_{k=1}^{\infty} J_{2k} \left( \frac{V_{AC}}{V_\pi} \pi \right) \cos(2k\omega_{AC}t) - \\ &- \alpha P_{in} \sin \left( \frac{V_{DC}}{V_\pi} \pi \right) \sum_{k=1}^{\infty} J_{2k-1} \left( \frac{V_{AC}}{V_\pi} \pi \right) \sin[(2k-1)\omega_{AC}t] \quad (6) \end{aligned}$$

Similar result can be found in [5] for instance. From the equation (6) formulas for computing the amplitude level of particular  $n^{\text{th}}$  harmonic component (7), (8) can be extracted.

$$P_{o-n-odd} = \left| \alpha P_{in} \sin\left(\frac{V_{DC}}{V_{\pi}} \pi\right) J_n\left(\frac{V_{AC}}{V_{\pi}} \pi\right) \right|, \quad (7)$$

where  
 $n \in \langle 1, 3, 5, \dots \rangle$

$$P_{o-n-even} = \left| \alpha P_{in} \cos\left(\frac{V_{DC}}{V_{\pi}} \pi\right) J_n\left(\frac{V_{AC}}{V_{\pi}} \pi\right) \right|, \quad (8)$$

where  
 $n \in \langle 2, 4, 6, \dots \rangle$ .

Presence of higher harmonic components in the spectrum of the output optical power reveals level of harmonic distortion. Total harmonic distortion is defined as a ratio of sum of higher harmonic components  $P_{on}$  to the fundamental  $P_{o1}$  (9).

$$THD = \frac{\sum_{n=2}^{\infty} P_{on}}{P_{o1}} \cdot 100 = \frac{\sum_{n=1}^{\infty} \left| J_{2n-1}\left(\frac{V_{AC}}{V_{\pi}} \pi\right) \right|}{\left| J_1\left(\frac{V_{AC}}{V_{\pi}} \pi\right) \right|} 100 + \frac{\sum_{n=1}^{\infty} \left| \cos\left(\frac{V_{DC}}{V_{\pi}} \pi\right) J_{2n}\left(\frac{V_{AC}}{V_{\pi}} \pi\right) \right|}{\left| \sin\left(\frac{V_{DC}}{V_{\pi}} \pi\right) J_1\left(\frac{V_{AC}}{V_{\pi}} \pi\right) \right|} 100 \quad (9)$$

Using the equation (9) the figure of harmonic distortion for given operating point set-up ( $V_{DC}$  voltage) and amplitude of modulating voltage ( $V_{AC}$ ) can be calculated.

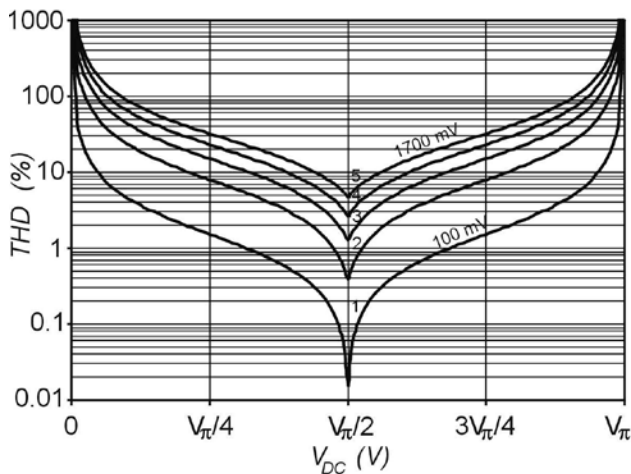


Fig.5 The MZM total harmonic distortion as a function of bias voltage  $V_{DC}$  (amplitude  $V_{AC}$  is a curve parameter)

Particular curves (1..5) in Fig.5 refer to fixed modulating voltages  $V_{AC}$  ranging from 100 mV up to 1700 mV with 400 mV steps. In spite of magnitude of  $V_{AC}$  the lowest harmonic distortion is evidently achieved at quadrature operating point  $V_{DC} = V_{\pi}/2$  (see Fig.5) and integral multiples of  $V_{\pi}/2$  (due to periodicity of transfer function (1)). Using (7) and (8) the dependency of the particular harmonic components as function of DC bias voltage can be depicted as well. The amplitudes of the first and second harmonics were depicted in Fig.6.

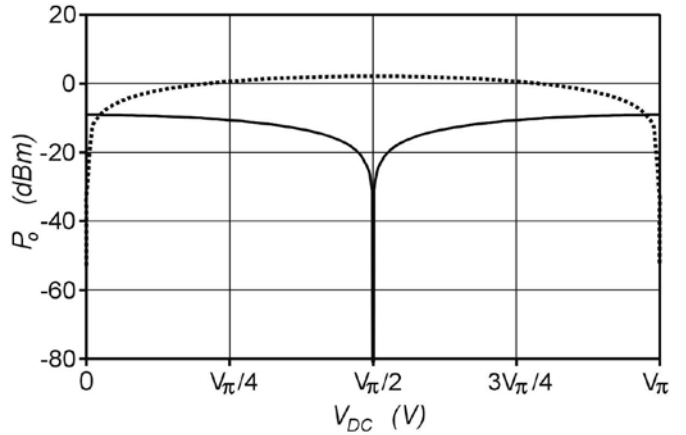


Fig.6 Dependency of 1<sup>st</sup> (dotted curve) and 2<sup>nd</sup> (solid curve) harmonics on DC bias  $V_{DC}$

The dependency of amplitudes of higher odd harmonics would demonstrate the same shape as the fundamental but with higher attenuation. Similarly, all the higher even harmonics would copy the shape of the 2<sup>nd</sup> harmonic component but with diminished amplitude. Fig.6 was depicted for input optical power  $P_{in} = 21.68$  mW, the modulator insertion loss  $\alpha = 0.5$  and modulating voltage  $V_{AC} = 500$  mV.

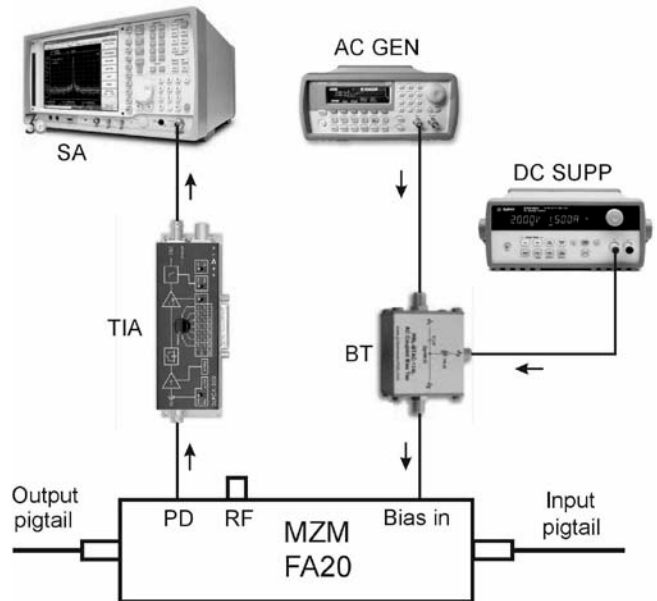


Fig.7 The system for the MZM operating point adjustment built-up of laboratory instrumentation

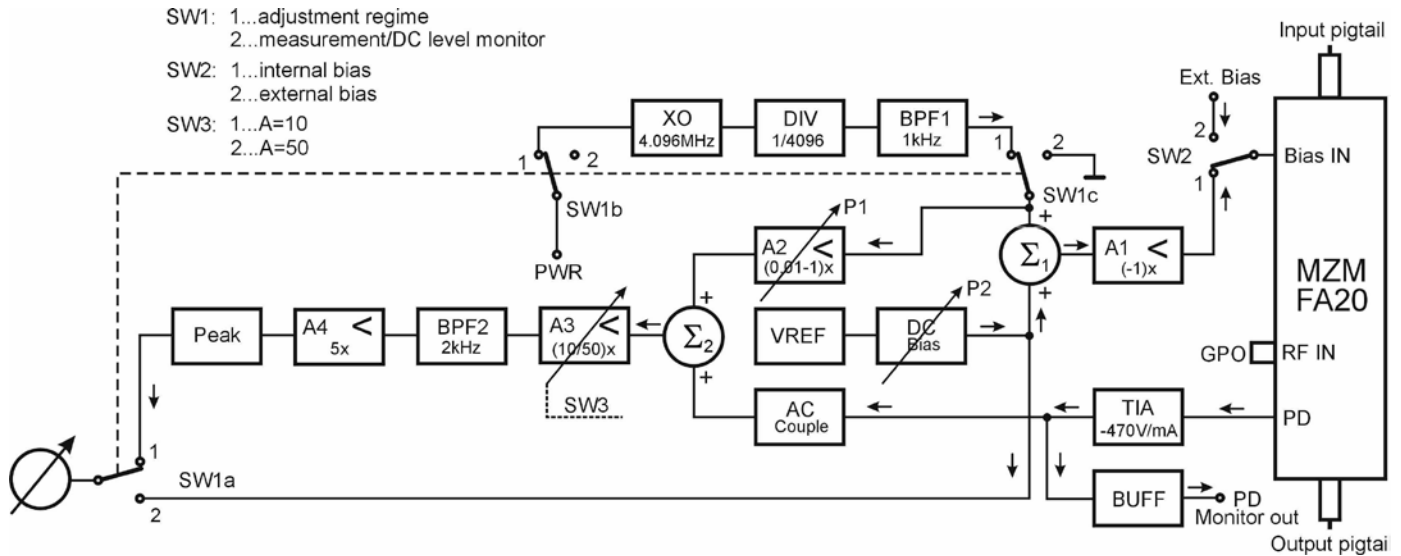


Fig.8 Block diagram of the designed bias driver

Magnitude of 2<sup>nd</sup> harmonic component reaches its minimum just at the desired quadrature point. If the quadrature point is reached the second harmonic virtually fades out. At the same time the total harmonic distortion reaches its minimum as well. Moreover, the second harmonic reflects the position of the operating point around the quadrature region with an extraordinary sensitivity. It brings the possibility to use the minimum of the 2<sup>nd</sup> harmonic component as an indicator of proper set-up. The proposed concept can be implemented using regular laboratory instrumentation (Fig.7).

Unfortunately, whole set of special purpose and fine laboratory instruments have to be used to build the system for operating point set-up. To generate pure enough harmonic signal a low THD function generator (AC GEN) is essential. DC power supply (DC SUPP) generating the bias voltage must be well stabilized and equipped with fine voltage regulation. Low frequency bias-tee (BT) must be used to couple DC and AC signals in front of the modulator bias input port. At the receiving side a trans-impedance amplifier (TIA) have to be used to convert the inner PD current to measurable voltage. Finally a spectrum analyzer (SA) to discover magnitude of 2<sup>nd</sup> harmonic component is necessary.

#### IV. THE BIAS DRIVER DESIGN

The 2<sup>nd</sup> harmonic component is the only part of the output spectrum that has to be tracked in order to achieve desired operating point. That is why, the rather clumsy and over-equipped concept proposed in Fig.7 can be reduced to single circuit based on proper filtration and amplification of input and output signals. The block diagram of proposed bias driver is depicted in Fig.8.

The bias input port of the modulator is excited by manually adjustable DC level and superimposed harmonic signal. The harmonic signal should have steady amplitude and frequency as well. Simultaneously, the inner PD of the MZM detects output signal of the modulator. Following circuitry analyses

presence of 2<sup>nd</sup> harmonic component in the spectrum of detected signal.

The DC level is generated by a voltage reference (VREF) and is manually adjustable by a block equipped with a precise 10-turns potentiometer (DC Bias). The AC part generates 1 kHz sinus signal with amplitude of 500 mV. Purity of the AC signal and especially absence of the 2<sup>nd</sup> harmonic component is important. That is why there was used method based on filtration of square wave signal. The crystal oscillator (XO) generates 4.096 MHz digital signal that is divided and shaped by a binary 12-stage ripple counter 74HC4040 (DIV). By the theory the spectrum of the generated square wave consists of odd harmonics only (Fig.9) and the problem of absence of second harmonic is resolved spontaneously then.

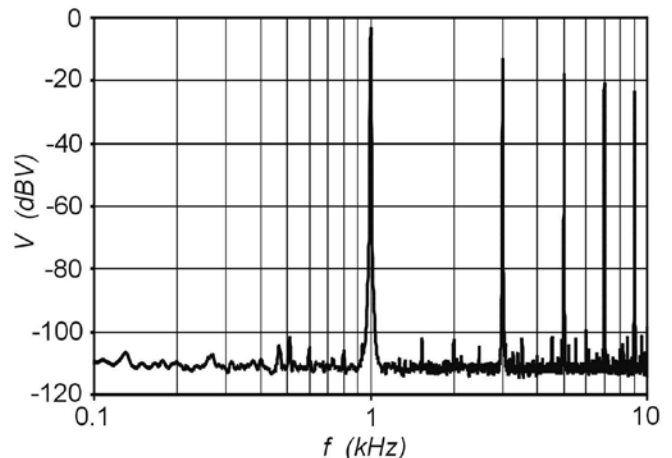


Fig.9 Spectrum of signal at the output of DIV block

The higher odd harmonics cut-off is done by narrow band-pass filter BPF1 with center frequency of 1 kHz. Various types of filters were tested there. Finally, there was chosen two-stage solution of 4<sup>th</sup> order filter using Butterworth approximation, Fig.10. To build-up the filter prototype a low distortion LMC6484 operational amplifiers were used.

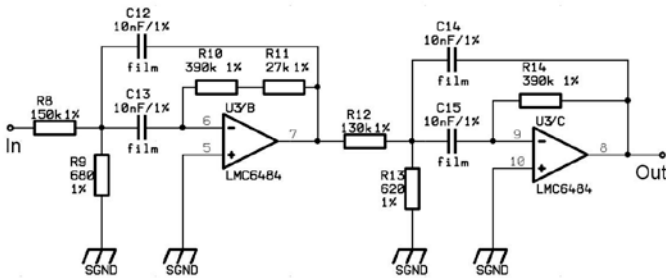


Fig.10 BPF1 filter tuned to 1 kHz

The filter demonstrates sufficient performance on expense of two operational amplifiers only. Suppression of more than 53 dB for 3<sup>rd</sup> harmonic (the nearest higher harmonic) and 65 dB for 5<sup>th</sup> harmonic is guaranteed by the filter (Fig.11).

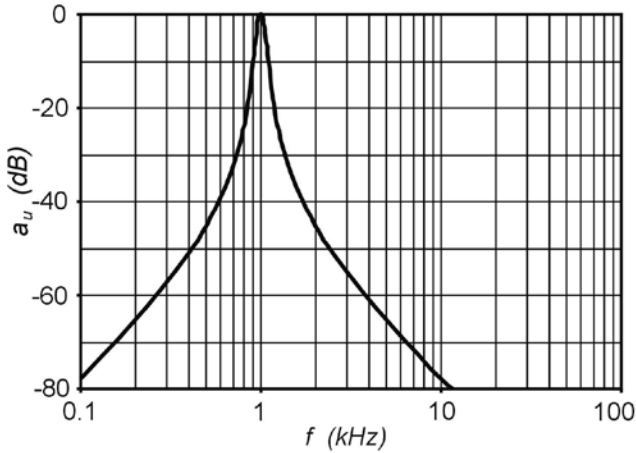


Fig.11 Frequency response of BPF1 filter tuned to 1 kHz

Spectrum of the AC signal at the output of BPF1 proves sufficient purity of the signal. The 3<sup>rd</sup> harmonic is suppressed to 65 dB below the fundamental. The 5<sup>th</sup> harmonic is suppressed to 81 dB below the fundamental. Nevertheless, for the needs of application the suppression of 2<sup>nd</sup> harmonic is most important. The 2<sup>nd</sup> harmonic is 84 dB below the fundamental.

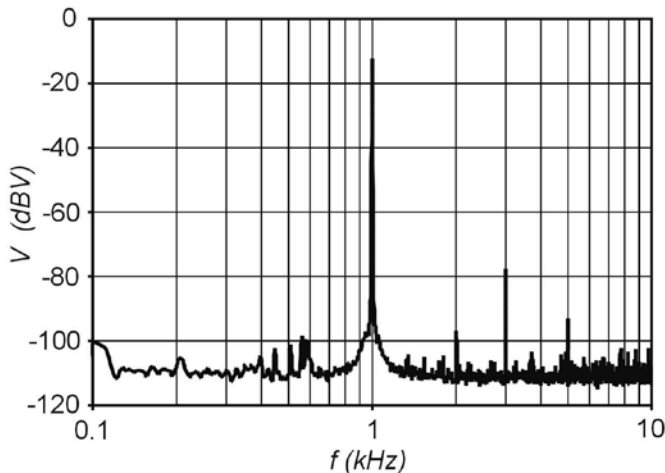


Fig.12 Spectrum of the generated AC signal delivered to the bias port input

The signal from BPF1 block is mixed with DC level from the DC Bias block by means of summing amplifier  $\Sigma_1$ . The following stage gives a 180° phase shift to the signal which is important for analysis of the signal detected by the inner photodiode PD.

The measuring chain starting with PD up to the deflective instrument was designed in order to analyze presence of 2<sup>nd</sup> harmonic in the output spectrum and visualize its magnitude. The inner PD of the MZM generates current that is inversely proportional to the output optical power of the modulator. This signal is converted to the voltage by means of trans-impedance amplifier (TIA). Gain of the TIA was experimentally set to -470 V/mA. The DC level of the TIA output signal is excluded by amplifier with integrating feedback (AC couple stage). To derive 2<sup>nd</sup> harmonic from the spectrum there is necessary to eliminate fundamental in received spectrum at first. This is carried out by summing amplifier  $\Sigma_2$ . Due to overall phase shift of the received signal the summing amplifier  $\Sigma_2$  works as a difference amplifier. At the output of the  $\Sigma_2$  the difference between the received AC signal and by the A2 stage attenuated exciting signal can be found. Actually, there have to be set-up level of attenuation of exciting signal leading to substantial decimation of fundamental at the output of  $\Sigma_2$  block. The point is clearly indicated by noticeable decrease of deflection of the measuring instrument. The signal is amplified by the A3 amplifier and filtered by BPF2 filter then. The BPF2 stage forms a band-pass filter tuned to 2<sup>nd</sup> harmonic regard to the exciting signal. The filter was designed similarly to BPF1 (4<sup>th</sup> order filter using Butterworth approximation implemented by LMC6484 operational amplifiers).

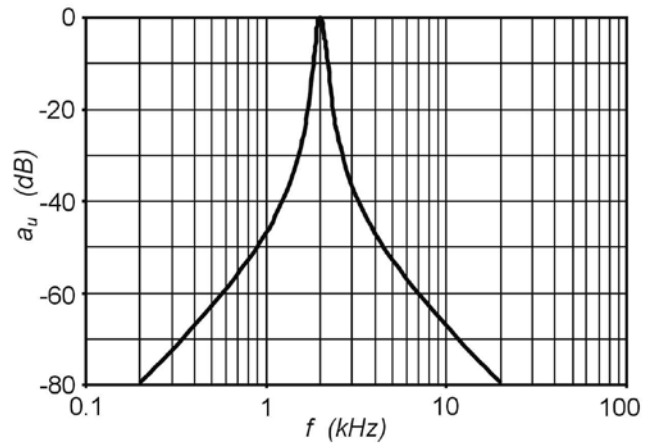


Fig.13 Frequency response of BPF2 filter tuned to 2 kHz

After an additional amplification in A4 block the signal is detected by a peak detector (Peak) and sent to the deflective measuring instrument.

### V. THE DRIVER CONTROL

Operation of the bias driver is controlled by five front-panel elements (two 10-turns potentiometers P1, P2 plus 3 switches SW1, SW2, SW3) and single needle indicator only. For set-up

regime the SW1 and SW2 have to be in position 1. The oscillator generates 1 kHz signal and the indicator measures magnitude of 2<sup>nd</sup> harmonic of PD signal. In case of considerable displacement of operating point (the indicator is saturated) the SW3 has to be switched to position 1 to allow coarse tuning at first. By adjustment of P1 element the fundamental rejection in received signal has to be achieved. The state is indicated by drop of the deflection of the indicator. In the next step the deflection has to be minimized again using P2 element. Subsequently, the gain of the A3 amplifier has to be increased (SW3 to position 2) to allow fine tuning and both of the previous steps should be repeated. Finally, the generator should be switched off (SW1 to position 2) to leave the adjustment regime and let the modulator bias port to be driven by the found DC level only. Simultaneously the indicator is automatically switched over to visualize the DC residuum.

## VI. RESULTS

The designed bias driver was implemented to the FA20 modulator forming a vital part of the specialized electro-optic modulating unit [6]. The operation correctness of the circuit was tested and verified by a spectrum analyzer. The modulator was excited by thermally stabilized laser source [7] and adjusted to the quadrature point by the designed bias driver. Subsequently, the spectrum of the signal at the BUFF stage output (PD Monitor Out) was measured. The measurements revealed -100.4 dBV magnitude of 2<sup>nd</sup> harmonic (i.e. -83.7 dB below the fundamental). By the driver found point is represented by minimum in Fig.14. By deliberate displacement of DC bias using gradual steps of  $\pm 10$  mV (P2) the rest of dependency depicted in Fig.14 was measured.

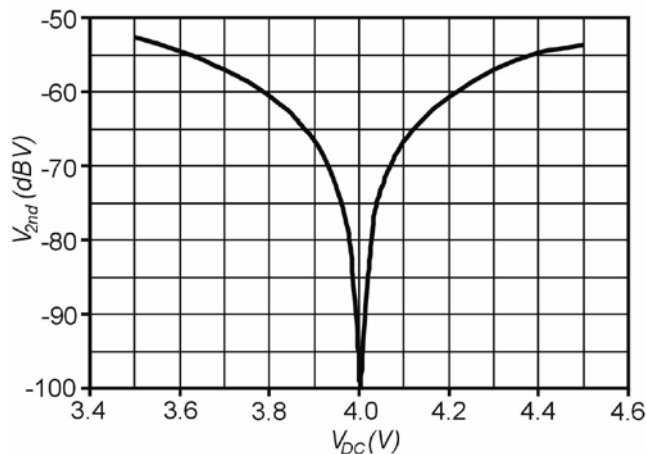


Fig.14 Dependency of 2<sup>nd</sup> harmonic measured at the PD Monitor Out in the proximity of detected operating point

The measured values were extracted from spectrums measured for particular DC voltages. The measurements of spectrums were carried out by means of low-frequency B&K Pulse<sup>TM</sup> analyzer working under the following set-up: DC-25.6 kHz span, 4 Hz step, averaging 200, Hanning window. Fig.14 proves that the bias driver is able to set-up the quadrature point with resolution of several mV.

## VII. CONCLUSION

The design of the bias driver and its verification confirmed the theoretical hypothesis. Harmonics performance of the MZM can be used as useful indicator of proper adjustment of the modulator operating point. The designed circuit represents a compact and effective alternative to rather clumsy and over-equipped concept based on conventional and costly laboratory instrumentation. Moreover, in comparison to the laboratory instrumentation based solution the designed bias voltage driver allows operative, safe and extremely precise adjustment of the operating point at the same time.

## REFERENCES

- [1] Avanex, Inc., "PowerLog<sup>TM</sup> FA-20, 20 GHz Analog Intensity Modulator with Small Form Factor", Data-Sheet, <http://www.avanex.com>
- [2] E. Ackerman, H. Roussel, C. H. Cox, "Bias Controllers for External Modulators in Fiber-Optic Systems", Photonic Systems, Inc. 2001, <http://www.photonicsinc.com>
- [3] A. Chen, E. J. Murphy, "Broadband optical Modulators - Science, Technology and Applications", CRC Press, 2012.
- [4] J. Svarny, "Analysis of quadrature bias point drift of Mach-Zehnder electro-optic modulator", In. Proc. BEC2010, Tallinn, Estonia, 2010, pp. 231-234.
- [5] A. Hilt, "Microwave harmonic generation in fiber-optical links", Journal of Telecommunications and Information Technology, vol.1/2002, pp. 22-28.
- [6] J. Svarny, "Specialized compact external electro-optic modulating unit", In. Proc. TSP2013, Rome, Italy, 2013, pp. 227-230.
- [7] J. Svarny, "Highly stable 20 mW infrared laser source", In. Proc. Applied Electronics 2009, Pilsen, Czech Republic, 2009, pp. 249-252.