Limited Applicability of the Constant Optical Power Controller to the Integrated Intensity Electro-Optic Modulator

JIŘÍ ŠVARNÝ
Department of Technologies and Measurements
University of West Bohemia
Univerzitní 8, Pilsen
CZECH REPUBLIC
svarny@ket.zcu.cz    http://www.zcu.cz

Abstract: - A bias drift is one of the issues facing the integrated intensity electro-optic modulators of Mach-Zehnder type. There have been developed several methods to compensate the drift. One of them is stabilization of an average output optical power of the modulator at constant value by means of suitable feedback. The paper deals with applicability of this method to the modulator equipped with integrated monitor photodiode working in radiating mode. An evaluation of efficiency of the method is presented here on basis of theoretical considerations and worked-out experiments as well. Surprisingly, the results reveal very limited applicability of the method in practice due to potential unreliability of optical connectors used to couple the light to the modulator.

Key-Words: - Electro-optic modulation, intensity modulation, electro-optic measurements, optical losses, optical communication, bias control

1 Introduction
The integrated LiNbO$_3$ analogue intensity modulator of Mach-Zehnder type (MZM) is undoubtedly a very efficient component of up-to-date high frequency and broadband electro-optic systems. Unfortunately, complex combination of pyroelectric, photorefractive, and photoconductive effects take action in LiNbO$_3$ substrate [1]. This leads to a drift of operating point. A gradual degradation of the MZM performance and whole the electro-optic system can be observed if the issue is not treated well [2]. Provided the modulating signal is DC component free the problem can theoretically be solved by automatic adjustment of DC bias voltage based on stabilization of the average value of output optical power.

Optical tap coupler is traditionally used to sample a small percentage of power exiting the MZM. The tapped light is directed to an external photodetector (PD) generating current, which is directly proportional to the optical power. The PD current is used as the input signal for bias controller. The controller drives the MZM bias voltage in order to keep the average value of the PD current at constant level. This method is well known including its limitations. One of the major drawbacks is inherent in lack of the immunity to instability of the input optical power which induces a bias error. The description of the effect as well as formula describing dependency of the bias error on input power variation for this configuration can be found in [3] for instance.

Up-to-date commercially available MZMs are usually equipped with integrated monitor PD, so the external tap coupler is no longer needed. In comparison to the previous approach the PD usually works in radiating mode. As the PD detects in LiNbO$_3$ absorbed light instead of the outgoing one, the PD current is indirectly proportional to the output power. However, that is not the main problem. The more trouble is probably caused by the fact that minimum PD current is not zero and its value depends on optical power incoming to the MZM.

The paper presents original theoretical considerations describing relations between input and output optical power fluctuations provided the MZM is biased by feedback system of type mentioned above, but using integrated monitor PD working in radiating mode. The final mathematical formula describing the bias error is presented here. To verify an applicability of the stabilizing method in this configuration an analogue bias controller was designed and implemented to the system. Subsequently, the performance of by the controller driven MZM was tested and evaluated. The experiments were performed using commercially available MZM with separated radio-frequency (RF) port, bias port and PD working in radiating mode, see Fig.1.

![Fig.1. Typical arrangement of integrated MZM](image-url)
2 Theoretical Background

In case of an ideal MZM excited in the bias port only (RF port is unplugged) the transfer function (black solid curve in the Fig.2.) can be described by equation (1).

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

where \( P_o \) and \( P_{in} \) is output and input optical power respectively, \( V_{bias} \) is voltage at the bias port, \( V_\pi \) is half-wave voltage of the bias port and \( \alpha \) is insertion loss of the MZM.

Fig.2. Impact of the bias drift to the transfer charts of the modulator

If the MZM module is equipped with monitor photodiode working in radiating mode (photo-current \( I_{PD} \) increases as the output optical power \( P_o \) decreases), it is possible to write the analogical formula describing dependency of photo-current on applied bias voltage (2) (see black dotted curve in Fig.2.).

\[ I_{PD} = \frac{I_{PD\text{max}} - I_{PD\text{min}}}{2} \cdot \left[ 1 - \cos \left( \frac{V_{bias}}{V_\pi} \pi \right) \right] + I_{PD\text{min}}, \quad (2) \]

where \( I_{PD\text{max}} \) and \( I_{PD\text{min}} \) is maximum and minimum photo-current respectively for particular input optical power. By means of derivative of the function (1) there can be obtained slope efficiency \( S_{MPq} \) value of the MZM power transfer chart at negative quadrature point (-Quad) (3).

\[ S_{MPq} = \frac{dP_o}{dV_{bias}} = -\frac{P_{in} \cdot \alpha \cdot \pi}{2 \cdot V_\pi}. \quad (3) \]

Similarly, respective slope efficiency \( S_{MIq} \) (4) of the PD current transfer function at negative quadrature point can be derived too.

\[ S_{MIq} = \frac{dI_{PD}}{dV_{bias}} = \frac{(I_{PD\text{max}} - I_{PD\text{min}}) \cdot \pi}{2 \cdot V_\pi}. \quad (4) \]

Grey curves (see Fig.2.) describe both the charts (output power and photo-current) affected by the drift. In case the bias port is driven by constant voltage source only the MZM operating point is likely to drift away from an ideal quadrature position. To prevent this behaviour the bias voltage should be automatically adjusted in proper way. Thanks to the symmetry of both the charts it seems to be sufficient to implement a feedback loop in order to keep the average value of \( I_{PD} \) at constant level \( I_{PD\text{opt}} \) and maintain the quadrature point stabilized. There is assumed that drift rate is relatively slow, modulating frequency (at RF port) is very high and modulating voltage has no DC component.

Unfortunately, this control method is unable to distinguish genuine drift of the MZM from input optical power fluctuations. The case is depicted in Fig.3. Grey curves describe output optical power transfer function (grey solid curve) and photo-current transfer function (grey dotted curve) affected by input optical power drop.

Fig.3. The operating point shift due to input power attenuation (system equipped with \( I_{PD} = \text{const. feedback} \))

\[ K_{in}-\text{coefficient represents a relative change (attenuation) of input optical power} \ (5) \ \text{either induced by optical source instability or as a consequence of momentary increase of insertion loss of input optical line.} \]

\[ P_{in} \xrightarrow{\text{attenuation}} K_{in} \cdot P_{in}, \quad K_{in} = \frac{P_{in} - \Delta P_{in}}{P_{in}} \quad (5) \]

Although there is no real drift in the case, there can be seen a drop of the photo-current and the output power as well. The feedback system adapts to a new state by means of change of \( V_{bias} \) trying to reach the original value \( I_{PD\text{opt}} \). Unfortunately, it leads to spurious shift of operating point \( \Delta \phi_{err} \) and change of output optical power.
from $P_{eq}$ by $\Delta P_{eq}$ to $P_{oerr}$ value. The invoked relative change of output optical power can be expressed by means of $K_{out}$-coefficient (6).

$$ P_{eq} \xrightarrow{\text{inv}} K_{out} \cdot P_{eq}, \quad K_{out} = \frac{P_{eq} - \Delta P_{eq}}{P_{eq}} \quad (6) $$

$K_{in}$ - $K_{out}$ relation was deduced using following considerations. Provided $I_{PDq}$ (original value of $I_{PD}$ for quadrature point set-up) is kept strictly constant thanks to the feedback loop, the equation (7) is valid.

$$ I_{PDq} = \text{const.} = \frac{I_{PDmax} - I_{PDmin}}{2} + I_{PDmin} = K_{in} \left[ \frac{I_{PDmax} - I_{PDmin}}{2} \left[ 1 - \cos \left( \beta + \Delta \phi_{err} \right) + I_{PDmin} \right] \right], \quad (7) $$

where $\Delta \phi_{err}$ is error shift of operating point. Furthermore, if the MZM is set-up exactly at the quadrature point the formula (8) is valid too.

$$ \frac{I_{PDmax} - I_{PDmin}}{2} + I_{PDmin} = \frac{\alpha \cdot P_{in}}{2} \cdot R_{PDq}, \quad (8) $$

where $R_{PDq}$ is well known responsivity of inner monitor photodiode at the quadrature point. Consequently, the $\Delta \phi_{err}$ value (9) can be derived from the equation (7) using the equations (3), (4) and (8).

$$ \Delta \phi_{err} = \arccos \left[ \frac{1 - K_{in}}{K_{in}} \right] \frac{\pi}{2}, \quad (9) $$

where $\beta$ (10) describes the way of radiation coupling to the monitor PD in case of the quadrature point set-up.

$$ \beta = \frac{S_{MPq}}{S_{MPq}} \cdot R_{PDq} \quad (10) $$

The relative change of input power $K_{in}$ induces a new value of output power $P_{oerr}$ (11).

$$ P_{oerr} = K_{in} \cdot P_{in} \cdot \frac{\alpha}{2} \left[ 1 + \beta \cdot \left( 1 - \frac{K_{in}}{K_{in}} \right) \right] \quad (11) $$

Consequently, it invokes relative change of output optical power $K_{out}$ (12).

$$ K_{out} = \frac{P_{oerr}}{P_{eq}} = K_{in} + \beta \cdot (1 - K_{in}) \quad (12) $$

Finally, the equation to compute $\Delta \phi_{err}$ as a function of $K_{out}$ (13) can be derived using (9) and (12).

$$ \Delta \phi_{err} = \arccos \left[ \frac{1 - \beta}{K_{out} - \beta} \right] - \frac{\pi}{2} \quad (13) $$

3 Experimental Part

The specialized base-board (MZM Unit) was designed to test the MZM performance. Apart from the MZM itself it consists of a pair of SC-SC optical adapters, battery power supply, reference source, bias port buffer, high gain broadband RF port driver (32 dB, 9 kHz – 3 GHz) and OP-amp based monitor photodiode trans-impedance amplifier (TIA). The gain of the TIA is $\pm 470$ V/mA.

The appliance was used to measure the MZM output power transfer chart, $P_{out} = f(V_{bias})$ and PD transfer chart, $I_{PD} = f(V_{bias})$. As optical source there was used thermally stabilized DFB laser (21.68 mW / 1550 nm) with output power long-term stability better than $\pm 0.009$ dB (3 hours) [4]. The measurements revealed following parameters: $V_{n} = 5.2$ V (@ bias port), $I_{PDmax} = 9.39$ mA, $I_{PDmin} = 3.87$ mA. Using the values in the formulas (3), (4), (10) together with well known data-sheet values ($\alpha = 0.5 (-3$ dB) and $R_{PDq} = 1.3$ $\mu$A/mW) it was possible to calculate: $S_{MPq} = -3.27$ mW/V, $S_{MPq} = 1.667$ $\mu$A/V and $\beta = -2.55$.

Subsequently, an analogue constant power bias controller (CPBC) was designed and connected to the MZM Unit. The circuit diagram of the controller is depicted in Fig.5. Basically it is a two-stage integrating controller with high integral gain. OP-amp U2 together with R9 and C7 components forms a traditional integrator. Gain of the integrator is considerably increased by means of the first stage (instrumentation amplifier U1). The U1 amplifies difference between the voltage at the output of the TIA (representing instantaneous value of the $I_{PD}$) and set-up voltage (representing desired average value of the $I_{PD}$). The position of desired operating point can be adjusted by...
trimming resistor R3. The U3A OP-amp limits the output voltage span of the controller. This precaution prevents from shifting the operating point of the MZM outside the positive slope region of the MZM transfer function. It maintains negative feedback of the control loop during the operation.

An operation of the modulator driven by the CPBC controller was tested by the measuring system sketched in Fig.6. An OMH-6810B optical multimeter equipped with OMH-6727B sensing head [5] was used to measure output optical power of the MZM. The multimeter disposes with analogue output generating voltage proportional to measured optical power. The voltage at the output was recorded by the DAQ system NI-USB-6221 driven by PC and LabVIEW application.

The DAQ system was used to measure TIA output voltage and controller output voltage \(V_{\text{bias}}\) as well. The measurements were carried out for a 3-hour-period at ambient temperature of 23±1 °C. All the parameters were recorded with sampling rate 1 Sa/s. Results are depicted in Fig.7., Fig.8., Fig.9. and Fig.10.
4 Discussion

The chart depicted in Fig.10. revealed that maximum measured fluctuation of output optical power $P_o$ of the MZM (in relation to original desired value of $P_{eq} = 5.3$ mW) is $\Delta P_o = -0.22$ dB ($K_{out} = 0.95$). Using formula (13) it translates to unacceptable operating point aberration of $\Delta \Phi_{om} = 2.1^{\circ}$. On the contrary, a view of $I_{PD}$ record (see Fig.7.) demonstrates almost rock-solid constant value ensured by the controller throughout the period. It is obvious that the $I_{PD}$ fluctuation of only $\pm 3$ nA around average value of 6.63 µA (see Fig.8.) can hardly justify such an extensive output power deviation.

Let us assume that the aberrations were caused by coincidental combination of instability of the optical source ($\Delta P_{DFB} = \pm 0.009$ dB) and random variations of insertion losses of optical connections $C_1$, $C_2$, $C_3$ (due to temperature, vibrations, etc.). All the optical connections were based on SC/PC connectors using plug-adapter-plug configuration.

In accordance with the equation (12) the final fluctuation of optical power $\Delta P_o$ detected by the multimeter sensing head can be described in dB by the formula (14),

$$\Delta P_o = 10 \cdot \log \left[ \beta + (1 - \beta) \cdot 10^{(\Delta I_{C1} + \Delta I_{C2} + \Delta I_{DFB}) \frac{1}{10}} \right] + \Delta I_{C3}, \quad (14)$$

where $\Delta I_{C1}$, $\Delta I_{C2}$, $\Delta I_{C3}$ represent insertion loss fluctuations of respective optical connections. If the measuring period is long enough and connections are of the same type the analysis can be simplified to the worst-case event (15) resulting in maximum output optical power fluctuation $\Delta P_{om}$ (16).

$$\Delta I_{C} = \Delta I_{C1} = \Delta I_{C2} = \Delta I_{C3}, \quad (15)$$

$$\Delta P_{om} = 10 \cdot \log \left[ \beta + (1 - \beta) \cdot 10^{(2 \Delta I_{C} + \Delta I_{DFB}) \frac{1}{10}} \right] + \Delta I_{C}, \quad (16)$$

The function (16) is depicted in Fig.11. The chart reveals, that even very tiny variation of insertion losses of the plug-adapter-plug connections (-0.023 dB in the case) has ability to induce high fluctuation of output power that was measured (-0.22 dB).

5 Conclusion

A needed MZM operating point stability depends on requirements of particular transmission system. For example analogue CATV optical links require stability better than $\pm 0.25^{\circ}$. The derived equations together with carried-out experiments revealed remarkable impact of insertion losses variations on movement of operating point of the MZM equipped with inner PD working in radiating mode. Now, it is obvious, that either more stable optical source or higher gain of the controller can hardly improve the operating point stability. Moreover, long-term variations of alignment of the optical connectors are likely to be even more severe in comparison to the value hypothetically deduced in this particular case. From this point of view, the bias control system of this type seems to be unsuitable for the MZM with integrated PD working in radiating mode.

The analysis did not take into account some additional effects that could make the considerations more complicated (optical fibre micro-bents, polarisation depending losses, etc.). Nevertheless, the results indicate that the stabilizing method would be applicable only if the laser source is coupled to the MZM input directly, i.e. without using any optical connectors and adapters.

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References: