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# Design and Construction Transceiver Module Using Polymer PLC Hybrid Integration Technology

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## 1. Introduction

Planar lightwave circuit (PLC) hybrid integration technology enables us to construct component by combining PLC with passive function (fiber and planar optical waveguides) and active optoelectronics devices (laser diodes, optical amplifiers and photodiodes) hybridized on a PLC (Hashimoto, T. & Nakasuga, Y., 1998). Recently, in foreign sources optical waveguides and hybrid circuits based on the polymeric materials such as the polymetametacrylate (PMMA), deutered ethylene glycoldimetacrylate, (for the wave length of 1300 nm) or pentafluoro-phenylmetacrylate (for the wave length of 1550 nm) or some type of the epoxy polymers and others optical materials including some glasses were investigated. (Eldada, L. & Shacklette, L.W., 2000).

The optical bidirectional transceiver module (TRx) is the key component for subscriber part of the passive optical networks (PON) for the fiber to the home (FTTH) topology. Our optical triplex TRx module has been designed with R Soft simulation programs and constructed by using a polymer PLC hybrid integration technology. The transceiver module consists of a planar polymer waveguides with a volume holographic grating triplex (VHGT) filter, surface-illuminated photodiode (SI-PD) and spot-size converted Fabry-Pérot laser diode (SSC-LD) in SMD package. An optical TRx module transmits a 1310 nm radiation upload and receives a 1490 nm download data as well as a 1550 nm download digital video signals for wavelength division multiplexing WDM cable TV application (Young-Tak, Yoon-Jung Park, 2006).

The optics TRx module was built on the polymeric material technological solution (PMMA and SU-8 2000 epoxy polymer) and the diagnostics of optical waveguiding structures for the integrated optics project and wants to develop the processes of the design of active photonic integrated structures further. As for selected theoretical issues dealing with the preparation of planar photonic hybrid integrated circuits, the works take up previously discovered major dependence of the index of refraction of selected polymeric thin layers on the electric field (Švorčík, V., Hüttel, I., Paláček, P.,2007) and using of this phenomenon at the production of planar channel optical waveguides.

First stage of the PLC design was to show how the radiation from the single mode optical fiber can be coupled to the planar optical waveguide. It allows making optical circuits on a planar substrate. The highly power efficient optical coupling between these devices is significantly important for determination of the planar waveguide attenuation.

The second stage will be a design and fabrication of the platform technology for hybrid PLC to match numerical aperture the waveguide made by organic polymer and SI-PD receivers or SSC-LD transmitter of the microwave optoelectronic transceiver TRx, which some subsection has been designed and simulated previously.

## 2. Design and results

### 2.1. Measuring and simulation of the optical elements

The first stage of our project was concentrated on design and coupling of the optical fiber to the channel optical waveguide and measuring attenuation. For this purpose, the 650 nm and 1550 nm wavelength semiconductor lasers were used. The radiation was coupled into a single mode optical fiber (SMF) which had a thickness core of 3.5 μm with a thickness cladding layer of 125 μm, the NA = 0.14 and its refractive index difference of 0.36 %; this fiber was matched to the channel waveguides by a piezoelectric driven micromanipulator to acquire sufficient position accuracy in the alignment process. When the desired alignment was achieved, the optical power meter for the measuring of the transmitted optical power across the waveguides was used. The optical waveguides were made from polymer Su-8 2000, lithium niobate or glass BK7. For fabrication of the channel waveguides in polymer was used spin – counting and UV exposition. The lithium niobate channel was fabricated by diffusion of Ti metal layers, the samples were cut to rectangular parallelepipeds and the channels were made by a conventional lithographic method. The samples of the bulk glasses were fabricated mixing the major components of glass ($SiO_2$, with $Al_2O_3$, $Na_2O_3$) with the network intermediates (MgO, CaO and/or ZnO). The channels waveguides for this glass were fabricated by $Ag^+ \leftrightarrow Na^+$ and $K^+ \leftrightarrow Na^+$ ion exchange. The most important characteristic of the samples is the attenuation. This attenuation is attributable to scattering, absorption and radiation. The attenuation of polymer SU-8 2000, glasses and lithium niobate optical waveguides were measured by the method end-fire coupling with waveguide of different length. The measurement is repeat for the large number of waveguide samples (in our case, we measured ten samples). The attenuation on to the waveguide can be determined from the relation (1) and the results of the measurement are given in Table 1.

| Channel waveguide | λ (μm) | Width (μm) | Height (μm) | Attenuation (dB/cm) |
|---|---|---|---|---|
| Su8 | 650 | 200 | 10 | 4.15 |
| Su8 | 1550 | 200 | 10 | 2.35 |
| BK7 | 650 | 6.8 | 7.0 | 0.499 |
| LiNbO₃ | 650 | 5.1 | 6.8 | 1.13 |

Table 1. Parameters of the optical waveguides losses

$$n = \frac{10 \log(P_2 / P_1)}{Z_1 - Z_2} \left[ \frac{dB}{cm} \right] \qquad (1)$$

Where P1 is output power sample with length $Z_1$ and $P_2$ is output power same sample with length $Z_2$ and $Z_1 > Z_2$.

The second stage of our research will be the design and fabrication of the platform technology for hybrid PLC to match the waveguide and microwave optoelectronic receiver, transmitter with SI-PD and SSC-LD element, which has been designed and simulated previously. The hybrid PLC has the two parts. The first part is the planar optical waveguide with a VHGT filter and collimation lenses, the second part is optoelectronic system with electrical microwave section. The optical part was realized by polymer layers optical waveguides or by microoptics. The polymer optical waveguides was deposited by using spin coating method on silica on silicon or GaAs substrate. As polymer we choose epoxy polymer NANO™ SU-8 2000 (SU-8 2000) from MicroChem Corp with cover layer PMMA. The optoelectronic element was fixed on a special metallic or alumina submount on the composite substrate. The VHGT filter is diffractive element with volume holographic gratings, which containing volume periodic changes index of refraction. The VHGT filter diffracts the 1550 nm and 1490 nm wavelength radiation into separate directions, while transmitting the 1310 nm radiation. When optical radiation incidents on holographic grating and satisfy Bragg phase condition, then happen to diffraction optical radiation for wavelength $\lambda_B$ of the transmission grating (2)

$$\lambda_B = 2 \Lambda \sin \theta \qquad (2)$$

where $\lambda_B$ is Bragg wavelength, $\Lambda$ is grating period and $\theta$ is angle of the diffraction. The simple schema of the VHGT filter is given on the Fig.1
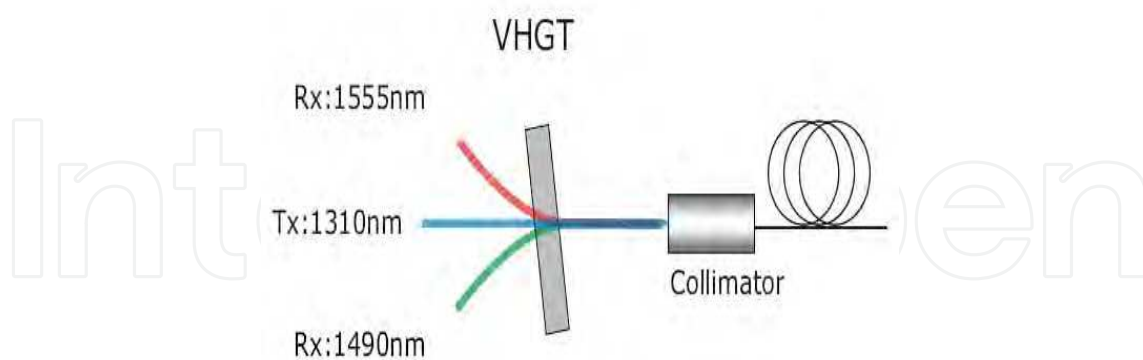


Fig. 1. Simple schema of the VHGT filtre arrangement

The diffraction angle of the VHGT filter was measured by the beam analyzing system Beam Profiler BP 104-IR from Thor Labs, see Fig.2.
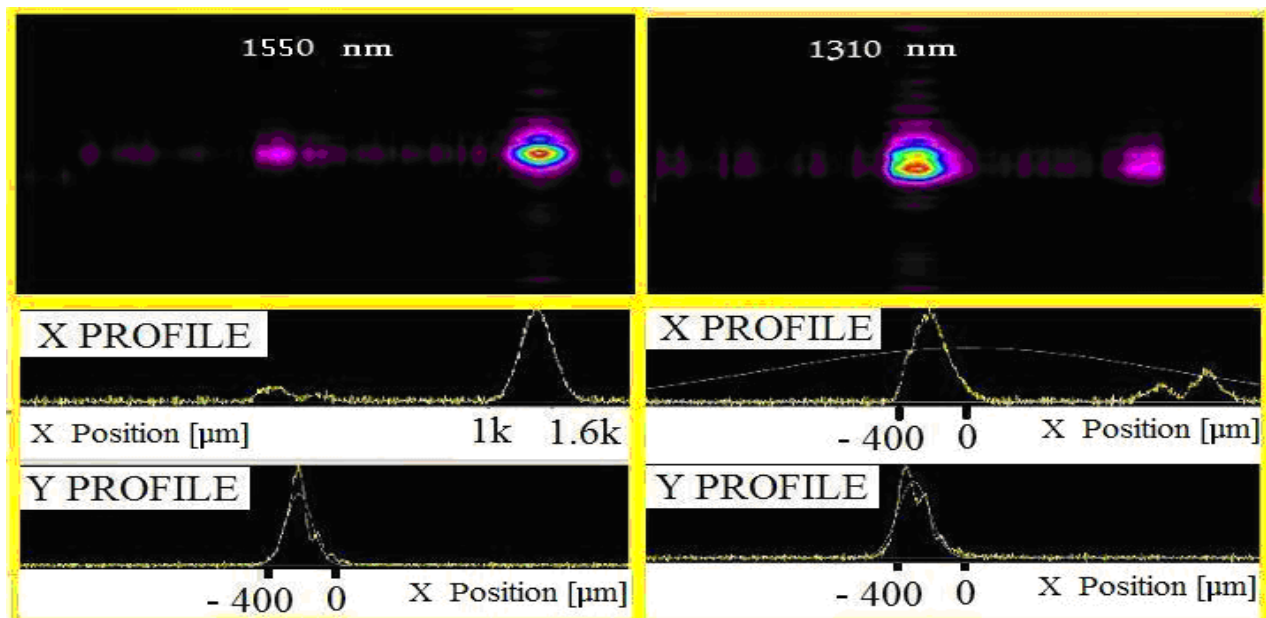
Fig. 2. The diagram of the diffraction angle measuring, which was determind as the radiation spot deflection in X-axis for the wavelength 1310 nm and 1550 nm as well as for 1490 nm. (The difference in Z-axis is 8 mm, difference in X-axis is 1.31 mm, diffraction angle is 19.3 degree for wavelength 1550 nm and zero degree for 1310 nm)

On the basis formula (2) was derived grating period $\Lambda$ = 2.388 µm. Further parameters of the VHGT filter were the temperature sensitivity 0.01nm/°C and insert losses max. 0.1 dB.

The optoelectronic part was created by two receivers with SI-PD PIN InGaAs photodiode chips on the alumina submount and transmitter with SSC-LD InGaAsP laser diode on metallic submount. The PIN photodiode and laser was placed in the groove for elimination height offset. The optimum distance among optical waveguides facet on base polymer SU8-2000 and optical fiber or PIN photodiodes in the receiving part was specified by BMP program with the waveguide facet width 100 µm and thickness 2 µm, buffer layer thickness was also 2 µm, refractive index waveguide layer $n_F$=1.596, refractive index buffer layer $n_B$=1.46, refractive index substrate $n_S$=3.5, wavelength 1550 nm. The cover layer of the optical waveguides was PMMA with thickness 5 µm and refractive index $n_C$=1,49. On the basis of the simulations in the program Beam Prop was derived the optimal distance of output facet optical waveguide and detection area photodiode 220 µm. The PIN photodiodes had antireflection coating (index of refraction n= 1.5 at 1550 nm).

The realization of the hybrid microwave integrated circuit of the photonic receiver was composed of a substrate from composite HF material Rodgers, polymer SU8-2000 optical waveguides with the ridge width 100 µm, thickness 2 µm and fast PIN photodiode in SMD package. The optimal distance measuring assessment between detector optical radiation and output facet optical polymeric waveguide placed in micromanipulator is shown in Fig.3. InGaAs PIN photodiode with the diameter active detection area 50 µm was used. The movement of PIN photodiode was controlled by handle micromanipulator with clamp clip. The optimal distance of PIN photodiode and output facet optical polymer waveguide 160 µm was measured. The differences of the simulated and measured value were given especially by error of the PIN photodiode and output facet waveguide distance measurement and accuracy of the multimode model used for simulation.
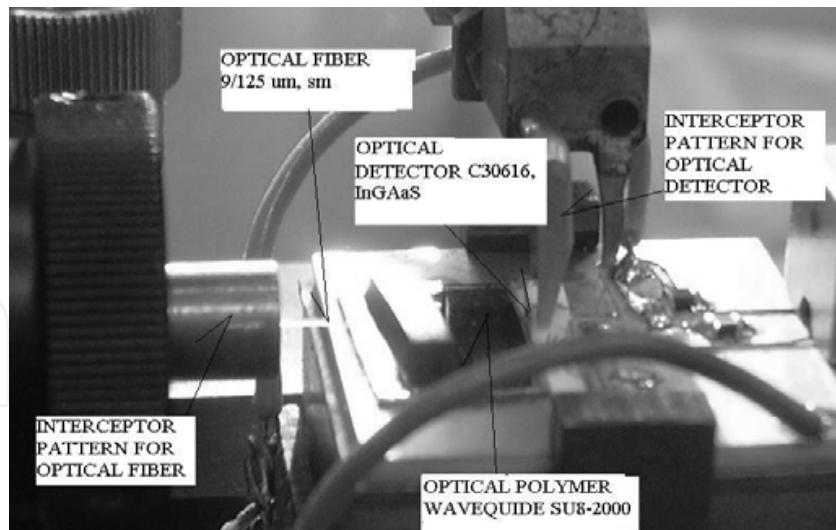
Fig. 3. Detail measuring setup for put optimal distance between optical PIN photodiode in SMD package and output facet of the planar optical polymer waveguide

The adjustment of the matching output PIN photodiode and the input microwave amplifier is necessary to achieve maximal responsivity and minimal losses in the electric transmission paths of the photonic receiver. The electrical part is made by thin layer hybrid microwave electrical integrated circuit. Our work was concentrated on design and construction of a microwave hybrid optoelectronic receiver (Jeřábek V.,Arciniega J.A., 2009), where the PIN photodiode was connected by microstripe line to input of the HBT amplifier. The all parts are placed on the composite material substrate.

## 2.2 Calculation

The theoretical analysis describes the microstrip connection between the PIN photodiode and the input of the HBT amplifier by the small signal equivalent circuit. For frequency response analysis we used the small signal equivalent circuit of the OE receiver input Fig. 4.
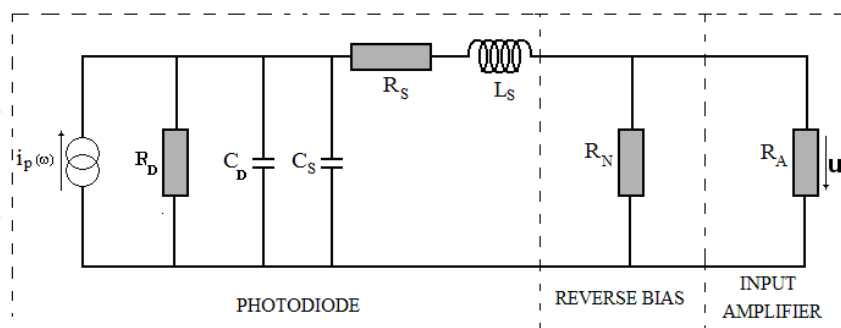


Fig. 4. The small signal equivalent circuit of the PIN photodiode with SMD assembly and input of the HBT amplifier

where
$i_p(\omega)$ – PIN photodiode photocurrent source
$C_D$ - capacitance of depletion layer 0.5 pF
$C_S$ - stray capacitance 1 pF
$R_s$ - series resistance 10 Ω
$R_D$ - dynamic resistance of the PIN photodiode 1 kΩ
$L$ - inductance generated by the photodiode SMD carrier
$R_N$ - thin film resistor for reverse bias voltage 2 kΩ
$R_A$ - input impedance 50 Ω of the ideal amplifier

The PIN photodiode (C30606ECER from Judson Technologies) chip connection to the microstrip waveguide is composed from compensation inductance made by gold microstrip on the alumina carrier $L_1$ and gold wire connection $L_2$. For calculation frequency response limit it was counted inductance $L$ given by (3).

$$L = L_1 + L_2 \tag{3}$$

For the cutoff angle frequency $\omega_T$ of the module complex transition $Z_T$ impedance characteristic (4) was derived

$$\left| Z_T \right| = \frac{R_D R_P}{\left[ \left( R_D + R_S + R_P - \omega^2 L C_D R_D \right)^2 + \omega^2 \left( L + R_D R_S C_D + R_D R_P C_D \right)^2 \right]^{1/2}} \tag{4}$$

The cut off angle frequency $\omega_T$ was derived as root of the transcendent equation (5)

$$\left| Z_T(\omega_T) \right| = \left| Z_T(0) \right| / 2^{1/2} \tag{5}$$

where $\left| Z_T(0) \right|$ is module of the impedance for $\omega = 0$, $R_P$ is parallel $R_A$ and $R_N$ combination.

The limit frequency $f_T$ received by solve equation (5) was $f_T = 2,78$ GHz. The module $\left| Z_T(0) \right| = 46,07$ Ω, $C_T = 1,5$ pF and L = 4,5 nH.
The optimum value of the inductance $L_{opt}$ for maximally flat transition impedance $Z_T$ characteristic is given after (Sackinger E., 2005) as (6)

$$L_{opt} = 0,4 R_T^2 C_T = 1,85 \, nH \tag{6}$$

The cut off frequency for optimum value $L_{opt}$ was calculated as $f_T = 3,25$ GHz.

The small signal equivalent circuit presented in the Fig. 4 was implemented for simulation in Win Mide program. The capacity of depletion layer $C_D$ is a function of reverse bias voltage and for 5 V is catalog value 0,50 pF. $C_s$ is stray capacity signal connection PIN photodiode SMD assembly. For good high frequency response it is essential to be $C_D$ and $C_s$ kept as low as possible. After that it is necessary to reduce $R_A$ or to provide high-frequency equalization. The inductance and capacity generated by the photodiode SMD carrier was simulated to analyze its influence on the device. The measured and simulated results $S_{21}$ frequency characteristic at the frequency range 0,1 – 3,5 GHz is shown in the Fig. 5.
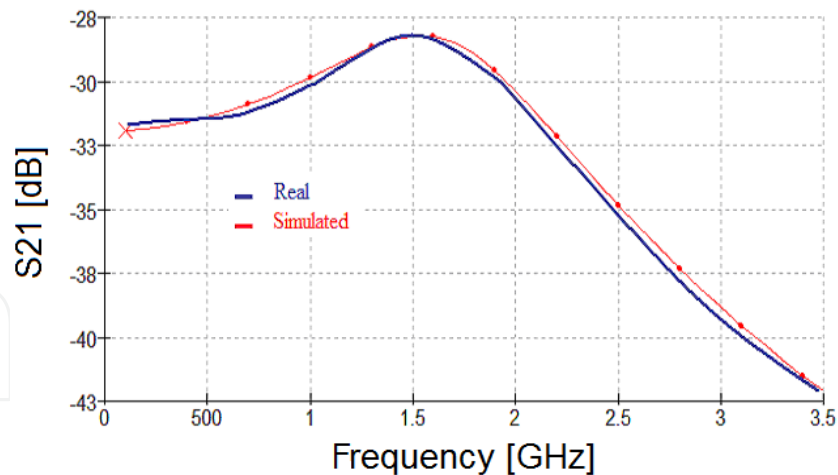
Fig. 5. The measured and simulated $S_{21}$ frequency characteristic of the OE receiver

The resonance of the lumped inductance $L$ in the signal way make the peaking effect in the $S_{21}$ frequency characteristic shift the bandwidth of the WDM receiver to 2,.5 GHz with acceptable ripple. For the transmitter was used spot-size converted Fabry-Perot laser diode (SSC-LD) for 1300 nm wavelength and monitoring surface-illuminated photodetector (SI-PD) for average optical power stabilization of LD in one SMD package. The optical bidirectional transceiver module TRx is given on Fig. 6. The transceiver module consists of a planar polymer waveguides with a VHGT filter with a collimation lens, SI-PD photodetectors and SSC-LD laser diode in SMD package. In the separate substrate of the bidirectional transceiver module electrical part was situated LD driver and optical power stabilized integrated circuits (IC) as well as IC HBT amplifier of the OE receiver.
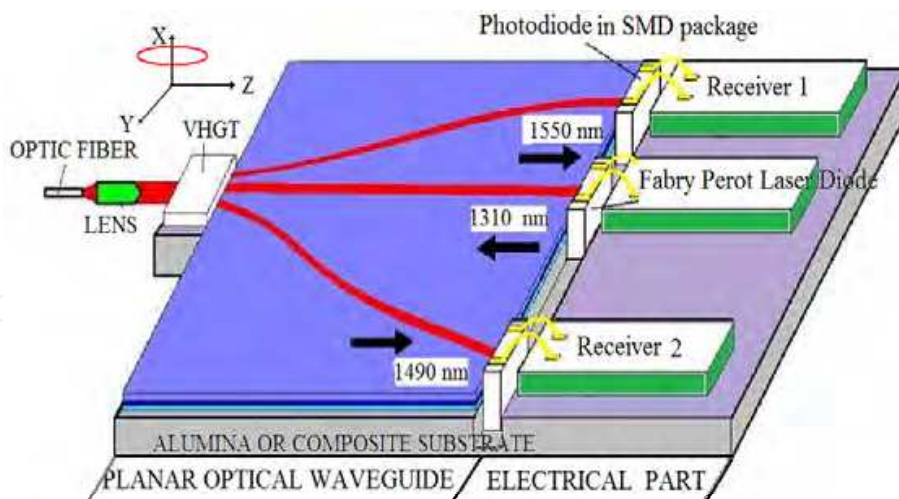


Fig. 6. The optical bidirectional transceiver module TRx

## 3. Conclusion

In this paper were presented first steps, which guide to the design and construction of a VHGT attached WDM triplex transceiver module TRx using polymer PLC hybrid integration technology. We report on the results measuring of the optical attenuation of the

SU-8 2000 epoxy polymer optical waveguides. The average attenuation of the waveguides made by polymer SU-8 was 4.15 dB/cm for 650 nm and 2.35 dB/cm for 1550 nm radiation, which is slightly higher than glasses and lithium niobate waveguides samples. We presented the diffraction angle measuring results of the VHGT filter between 1310 and 1550 nm wavelength which was 19.3 degree as well as 1490 nm.

The second step was design of the hybrid photonic planar integrated receiver with a polymer optical waveguide, InGaAs p-i-n photodiode and integrated HBT amplifier. The calculated coupling efficiency, for direct coupling to the input facet of the optical polymer waveguide (SU8-2000) with the SMF laser source optical radiation 1550 nm was 39 %, for fundamental mode $TE_0$. The difference among calculated and measuring results was given lower quality of the waveguide facets. The optimal distance between optical polymeric waveguide facet and p-i-n photodiode was simulate in program Beam Prop. The simulation was optimized to maximum transfer optical power. The optimal distance of the output facet optical waveguide and the detection area photodetector was 220 μm. The verification of the optimal distance was made by measuring with seven axis system micromanipulator at 160 μm. The measurement differences are given by the error of the measuring system and multimode model used for simulation. The above mentioned results were used for the design fundamental masks of the photonic receiver. Further work will be concentrated on design and construction of optoelectronic transmitting part, which will be fabricated by use existing technology with bandwidth 2.5 GHz as the main optoelectronic part of the hybrid PLC integrated microwave transceiver TRx for the FTTH topology optical PON networks.

## Acknowledgements

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