MODELING KEY PHOTONICS COMPONENTS BASED ON OFF-THE-SHELF MICROWAVE-ELECTRONICS COMPUTER TOOL

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ABSTRACT
We review our known, updated, and newer models and simulation results using power microwave-electronics off-the-shelf computer tool NI AWRDE to pursue advanced performances corresponding to the last generation of key microwave photonics components. As a result, we proposed and validated experimentally a new approach to model a broad class of promising analog microwave radio-electronics systems based on microwave photonics technology.

Keywords: microwave photonics, nonlinear equivalent models, microwave-band optoelectronic circuitry elements, computer aided design

1. INTRODUCTION

The modern optical fiber is the information transfer medium for telecom fiber-optics system (TFOS) and has unique operation features, combining low losses and dispersion of the propagating signal, insensitivity to electromagnetic interference, long life cycle and economic feasibility. Thanks to these features, the TFOS's global backbone networks currently exceed 70% of all existing communication facilities. In addition, growing significantly annual demands to transferred information volumes and reduction of delivering time, force hardware developers to constantly capacity increase of this TFOS class in order to use optimally quartz-based optical fiber bandwidth up to its limit that is tens of terahertz (O'Mahony 2006). However, the above-mentioned advantages of TFOS are less obvious in modern local information and communication networks (ICN) of various functionalities. A typical examples are data center (DC) access networks, as well as rapidly developing multi-service subscriber access networks with relatively short (from several meters to 10-15 km) transmission links and much higher requirements to the cost of building and maintenance. In particular, it is impossible to satisfy by TFOS the above requirement to provide communications with mobile subscribers.
Solution of this problem led to the emergence of hybrid local ICNs of radio-over-fiber (RoF) architecture, which combine the fiber-optic and wireless systems

2. MODELS OF MICROWAVE PHOTONICS-BASED CIRCUITRY ELEMENTS

2.1. Semiconductor Laser

A semiconductor laser is one of the most important circuit elements for both fiber-optics and integrated MWP devices, performing the function of electro-optical conversion. Earlier, for simulation of optoelectronic microwave units, we proposed and described in detail (Belkin, Iakovlev 2015) a non-structural (in the form of an equivalent electric circuit) nonlinear model of the laser (Figure 1), suitable for developers of modern analogue fiber-optics systems with a sub-carrier band in the radio-frequency (RF) range, local telecommunication systems of RoF architecture, devices of microwave optoelectronics, as well as optical interconnects in the integrated circuits.
However, the proposed single-band (combined RF and optical bands) model will be correct only in the case of direct modulation of a laser by a microwave signal, but it will be ineffective for modeling MWP device with external modulation and is completely unsuitable in the case for modeling of MWP-based ARES operating on several optical carriers. To investigate such units, an improved dual-band (separated RF and optical bands) laser model with two input ports is proposed (Figure 2), one of which simulates an optical carrier and the other one - a modulating microwave signal. Such an approach is correct for a computer working at the symbolic level.

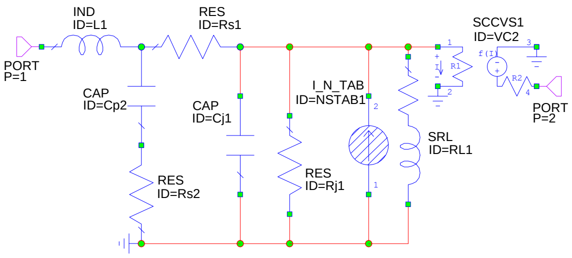

Figure 1: Equivalent electric circuit nonlinear model of the semiconductor laser

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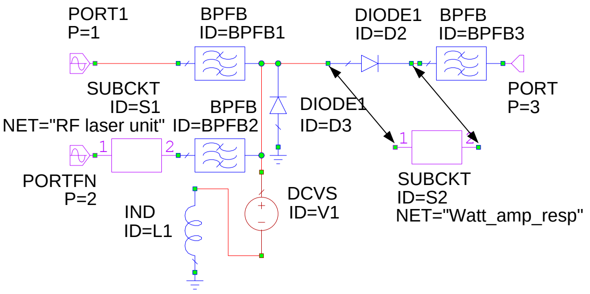
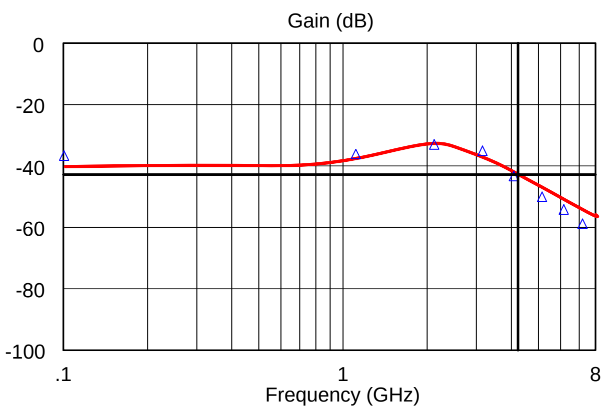


Figure 2: Improved dual-band laser model

The nonlinear models of a laser have been developed make it possible to calculate their key dynamic characteristics with simple and high accuracy, both in the small-signal modulation mode (gain characteristics, standing wave voltage ratio (VSWR), relative intensity noise (RIN)) and in large-signal mode (harmonic and intermodulation distortions, intercept point, dynamic range) that cannot be estimated using optoelectronic CAD tool. As an example, the results of the calculation and experimental verification of small-signal gain characteristics for two bias currents of vertical cavity surface emitting laser (VCSEL) corresponding to a double (a) and five-fold (b) exceeding of its threshold current value are shown in Figure 3. From the Figure one can draw the following conclusions:

- the gain factor is -37 dB, which corresponds to the VCSEL's typical parameters (Piprek and Bowers 2002);
- the -3-dB modulation bandwidth is 4.2 GHz at a bias current 4 mA and increases to almost 8 GHz at a current of 10 mA, which corresponds to the typical tendency (Piprek and Bowers 2002);
- the discrepancy between the calculated and experimental data in both cases does not exceed 2%, which indicates the validity of the proposed model.



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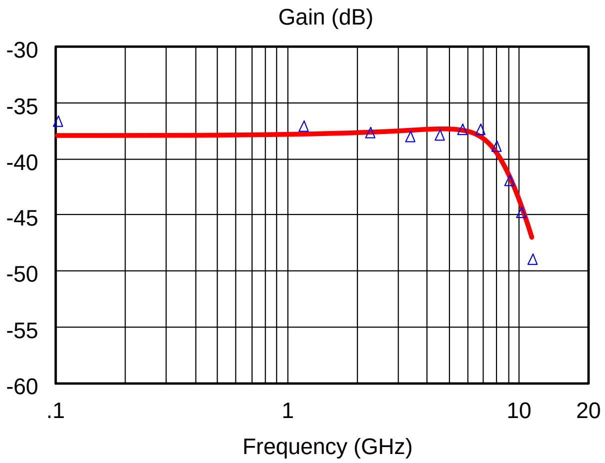


b)

Figure 3: Calculated (solid lines) and measured (triangles) gain characteristics of the laser under test

2.2. Photodiode

Another principal component, which should terminate each MWP circuit, is a semiconductor photodiode that performs the function of optical-electrical conversion. The original version of equivalent-circuit nonlinear model of a photodiode with a microwave bandwidth was proposed and described in detail in (Belkin 2012). Recently, an improved model of a photodiode (Figure 4) with updated parameters for a p-i-n photodiode with a passband of 40 GHz was developed (Belkin, Sigov 2015).

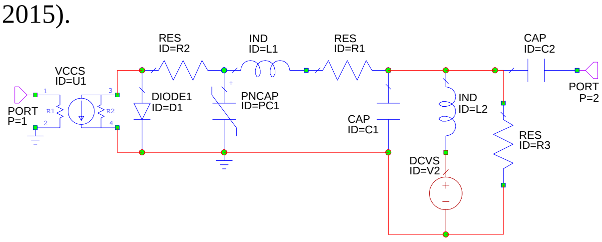


Figure 4: Improved model of a photodiode (Belkin, Sigov 2015)

The nonlinear model of a semiconductor photodiode has been developed allows to calculate its key dynamic characteristics with high accuracy, for example, the frequency characteristic, the linearity of the optical-electrical conversion in the large-signal mode, which cannot be estimated with the help of any available optoelectronic CAD tool. The latter characteristic is especially important for the purposes of MWP, so its study was focused on in our analysis. As is known, the linearity of the optical-electric conversion of a photodiode, which, like for a laser, is determined in terms of intermodulation distortions (IMD) and is affected by its operating mode: in particular, the depth of RF modulation of the optical carrier, the magnitude of the reverse DC bias (Urick, McKinney, and Williams 2015). For example, Figure 5 depicts the results for third-order IMD modeling at two frequencies at 10.0 and 10.1 GHz of a p-i-n photodiode with vertical illumination and a passband of about 40 GHz at a reverse bias of 1 V for three values of the modulation depth of the optical carrier of 10, 25 and 80%.

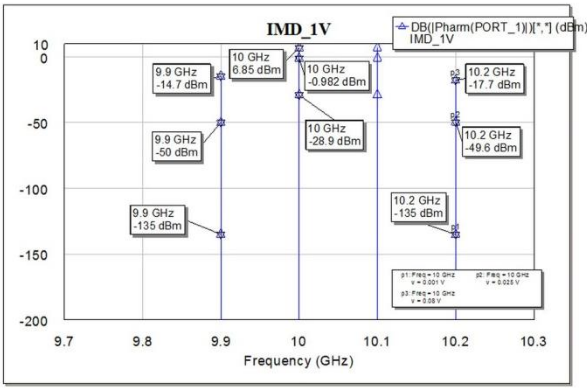


Figure 5: The calculated characteristics of the third-order intermodulation distortions of the photodiode under study at different values of the modulation depth

For convenience of an estimation the received numerical data are listed in Table I, which also includes the results of an experimental study.

Table I: Dependence of intermodulation distortions on the depth of optical modulation

Optical modulation depth (%)	Third-order IMD (dB)	
	Calculation	Experiment
10	< -100	<-80
25	-49	-48
80	-23	-21,5

The following conclusions can be drawn from the Figure and the Table:

- modulation depth up to 25% ensures acceptable linearity of optical-electrical conversion, which corresponds to the photodiode's typical characteristics (Urick, McKinney, and Williams 2015);
- if this value is exceeded to increase the signal-to-noise ratio, the level of intermodulation interference sharply increases, which is correct for any nonlinear circuit;
- the discrepancy between the calculated and experimental data does not exceed 1%, which indicates the validity of the proposed model.

2.3. Electro-Optical Modulator

Despite the simplicity, the direct intensity modulation of a semiconductor laser, which was widely used at the early stages of the TFOS development, has a number of drawbacks: a limited modulation band (up to 18 GHz), parasitic frequency modulation (chirp), necessity of rigid stabilization for the operating point, and so on. In this reason, a remarkable development acquires external intensity modulation, for which a modulator based on a Mach-Zehnder interferometer (MZM) is commonly used. Figure 6 depicts the newer developed MZM nonlinear model based on the equivalent circuit realized in the Schematic environment of AWRDE tool with a carrier at the optical frequency and a modulation signal at the radio frequency.

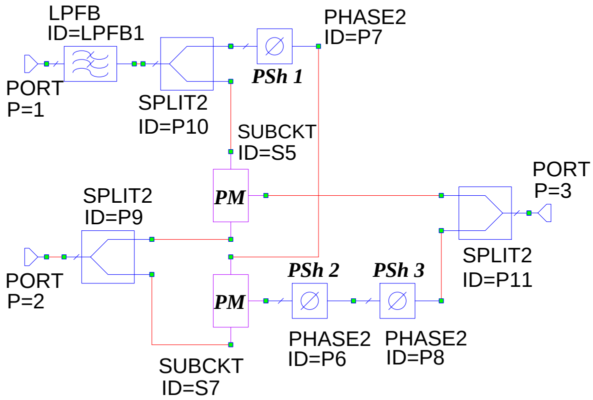


Figure 6: Equivalent circuit-based nonlinear model of Mach-Zehnder optical modulator

The design principle of the model fully reflects the building principle of the MZM (Urick, McKinney, and Williams 2015). Namely, a continuous signal from equivalent quasi-optical port 1 splits in two arms. Each of them includes electrically controlled by antiphase RF signals phase modulator (PM), which model is shown in Figure 7. The core element of both models is the phase-shifting cell (PSC). Figure 8 shows the equivalent circuit of PSC, in which the phase shift is provided by the nonlinear capacitance of the library model of the variable capacitor VRCTR.

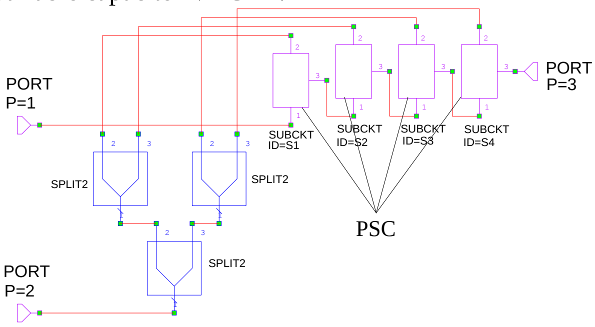


Figure 7: The model of phase modulator based on four sub-models of phase shifting cell

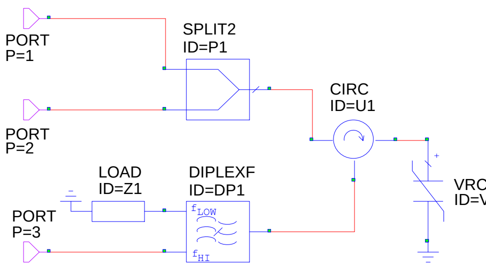
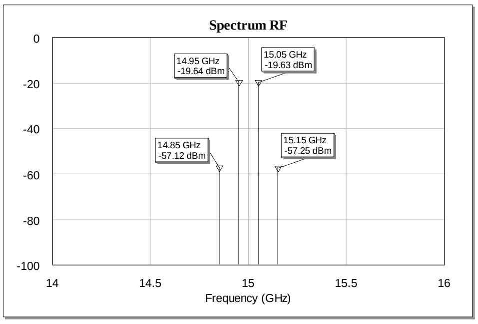


Figure 8: The model of phase shifting cell

The model of the MZM has been developed allows simple and high-precision calculation of its key static and dynamic characteristics. An important feature of the proposed model is its non-linearity that results in possibility to determine a number of large-signal parameters for a microwave MWP unit, such as 1-dB compression power P_{-1dB} or third order intercept point *IIP3*. The latter is determined from the transmission characteristics of the MZM at the fundamental modulating frequency and the frequency of third-order intermodulation distortions (IMD3) under two-tone impact. Note that these key quality parameters cannot be calculated using any optoelectronic CAD tool, but in AWRDE, these model experiments are performed by a one-button operation.

Modeling and real experiments were performed in the same modes when an unmodulated signal with an output of the order of 50 mW at a frequency of 193.3 THz was applied to the optical input of the modulator. Besides, a single sinusoidal RF signal with a frequency of 15 GHz during the P-1 dB test or two sinusoidal RF signals with frequencies of 14.95 and 15.05 GHz during the IIP3 test were applied to its modulating input. In both cases, the power range of the input RF signals corresponded to -15 ... 15 dBm for the calculation and -15 ... 10 dBm for the experiment. The constant bias of the MZM tested was established at the quadrature point of its transfer characteristic. Figure 9 exemplifies the results of calculation (a) and experiment (b) for third-order IMD levels at RF signal power on a modulation input of 10 dBm. The *IIP3* level calculated based on the obtained data was approximately 28 dBm, experimentally determined - 26 dBm. The calculated compression point of the P_{-1dB} is approximately equal to 14 dBm, determined experimentally - about 12 dBm.



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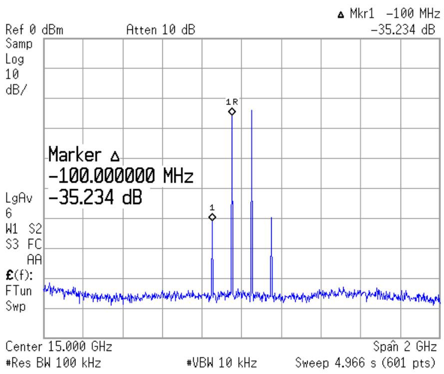

b)

Figure 9: Third-order intermodulation characteristics of the optical modulator under test

From the Figure and the subsequent calculations, we can draw the following conclusions:

- levels of *IIP3* and P_{-1dB} correspond to the MZM's typical parameters (Urick, McKinney, and Williams 2015);
- the discrepancy between the calculated and experimental data does not exceed 2 dB, which indicates the validity of the developed model even with modulation in the large signal mode.

3. CONCLUSION

In the paper, we described the results of development for behavior models in the form of physical equivalent circuits, as well as model experiments to calculate the key characteristics of the main microwave photonics components using well-known off-the-shelf microwave-electronics CAD tool AWRDE (National Instruments). The validity of the proposed models was confirmed by the results of experimental studies.

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