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SELECTING AN OPTIMAL COMPUTER SOFTWARE TO DESIGN MICROWAVE-BANDWIDTH OPTOELECTRONIC DEVICES OF A FIBER-OPTICS LINK

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ABSTRACT
Selecting an optimal program mean, we compare in detail two off-the-shelf computer-aided design software: optoelectronic VPIphotonics Design Suite and microwave-electronic NI AWRDE by designing a realistic microwave-photonics-based fiber-optics link including two widespread microwave-bandwidth optoelectronic devices at the transmitting end such as direct intensity modulating semiconductor laser and external intensity modulating electro-absorption modulator. In the result, the qualitative comparison of possibilities showed that NI AWRDE-based approach generally provides broader and deeper functionality, and the single critical shortcoming of it is the absence of any built-in photonic models. Nevertheless, the quantitative comparison on the example of transmitting 2.5 Gbit/s 16-QAM signals at radio-frequency carrier of 25 GHz along the same fiber-optics link showed a relatively close coincidence for the quality of digital radio signal transmission, which indicates the possibility of modeling in any of the software environments.

Keywords: microwave photonics, fiber-optic link, computer-aided design, directly modulated semiconductor laser, electro-absorption modulator

1. INTRODUCTION

It is well-known that Radio-over-Fiber technology, RoF (Al-Raweshidy, Komaki 2002; Novak, Waterhouse, Nirmalathas, Lim, Gamage, Clark, Dennis and Nanzer 2016; Bakhvalova, Belkin, Fofanov 2018) should find the most extensive dissemination to architect an access network in the incoming mobile communication systems of fifth generation, 5G NR (Andrews, Buzzi, Choi, Hanly, Lozano, Soong, Zhang 2014; Chen, Zhao 2014; Waterhouse and Novak 2015), and a microwave-photonics-based (Seeds and Williams 2006; Capmany and Novak 2007.) fiber-optics link (MP-FOL) is a requisite part of this technology. Devices of microwave photonics (MWP) operate concurrently in microwave and near infrared (optical) bands, thanks to it they are finding a widespread occurrence in modern radio engineering means related with information traveling, monitoring of environment and technological parameters of production, radar supervision, etc. Nowadays there are specialized optoelectronic computer-added design (OE-CAD) tools allowing to develop and simulate both radio-frequency (RF) and optical circuits separately or in common. However, in the latter case, which is inherent for MP-FOLs, the structural, functional, and parametric restrictions of either optical or RF range are inevitable. For example, by well-known OE-CAD environment VPI Photonics Design Suite a developer is able to execute in precision manner the design of a fiber-optic link with detailed study of optical units' characteristics, but RF, especially microwave and millimeter-wave functional devices or units are designed without paying attention to specialties of microwave band. On the other hand, operating at symbolic level modern high-power microwave electronic CAD (E-CAD) tool is able simply and with high precision to solve this problem but there are completely no models of active optoelectronic devices in its libraries.

Recently, we proposed and described a way to overcome this problem and encourage an accurate design of MWP-based radio-electronic devices and systems using, for example off-the-shelf E-CAD tool NI AWRDE (Belkin, Golovin, Tyschuk, Vasil'ev, and Sigov 2018). Following it, in this paper we compare E-CAD and OE-CAD tools by designing a realistic MP-FOL including two widespread microwave-bandwidth optoelectronic devices at the transmitting end such as direct intensity modulating semiconductor laser (DIM-SL) and external intensity modulating electro-absorption modulator (EIM-EAM). So, the remainder of the paper is organized in such a way. First, the microwave photonics approach and the available OE-CAD and E-CAD software are highlighted shortly in sections 2 and 3, correspondingly. Then in section 4, the models and setups for simulation using VPI Photonics Design Suite and NI AWRDE software are proposed and discussed. Section 5 represents the simulation experiments and results referred to transmitting 2.5 Gbit/s 16-QAM signals at RF carrier of 25 GHz over MP-FOL using the single-mode optical fiber of various distances. Section 6 concludes the paper.

2. MICROWAVE PHOTONICS APPROACH

Microwave photonics is an interdisciplinary scientific and technological area that combines the domains of microwave and RF engineering and photonics (Urick, McKinney, Williams 2015). This direction in the last 40 years has attracted ever-increasing interest and generated many newer R&Ds from both the scientific community and the commercial sector. Emerging applications for 5G NR networks based on RoF architecture, sub-terahertz wireless systems, radar, and electronic warfare means indicate that MWP approach is set to be a subject of great importance. Generally, MWP devices are the examples of an intimate integration of photonics, microwave electronics, and antenna array technologies for producing a complicated functional module in a multichannel analog environment. In particular, MWP technique opens the way to super-wide bandwidth transmitting characteristics at lower size, weight, and power as compared with traditional electronics (Paolella, De Salvo, Middleton, and Logan 2015). As an example, in a typical arrangement of MWP-based fiber optics link (Figure 1), a photonic area is inserted between two microwave-electronic areas. The first one includes RF transmitter unit that typically consists of a digitally modulated data source, RF up-converter, and RF power amplifier, while the second one includes RF receiver unit that typically consists of a low-noise RF amplifier, RF down-converter, and data detector. For forward and reverse transformations of microwave and optical signals there are two interfacing units at their bounds: electrical-to-optical (E/O) and optical-to-electrical (O/E) converters. E/O-converted microwave signals are distantly transported in optical domain through optical fiber.

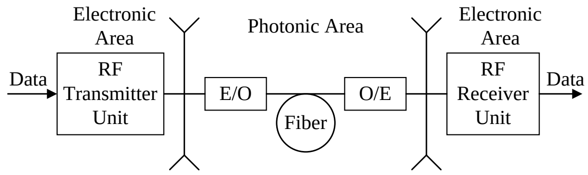

Figure 1: A Typical Arrangement of MWP-Based Fiber-Optics Link

3. AVAILABLE OPTOELECTRONIC AND MICROWAVE ELECTRONIC SOFTWARE

The developer of new MWP devices is facing a problem of choosing an appropriate computer tool for their modeling and design. As of today, a system designer is forced to use means of several computer-aided design tools because the existing OE-CAD are not as developed as compared with the E-CAD tools intended for modeling of microwave devices (Leijtens, Le Lourec, Smit 1996). Table 1 lists detailed comparison of two off-the-shelf software: OE-CAD tool VPI Photonics Design Suite of VPI Photonics and well-known E-CAD tool AWRDE of National Instruments. As one can see from the Table, the second approach generally provides broader and deeper functionality; and the single critical shortcoming of E-CAD tool is the absence of any built-in models of photonics area interfacing elements (see Figure 1).

Table 1: Comparison of Modern Off-The-Shelf E-CAD and OE-CAD Tools

#	Feature	Realization		Comments
		By E-CAD (NI AWRDE)	By OE-CAD (VPI Photonics Design Suite)	
1	Analysis approach	Building Blocks, 3D electromagnetic analysis	Building Blocks	Broader and deeper functionalities of E-CAD
2	Simulation methods: - Linear circuits -Nonlinear circuits	S-,Y- matrix, equivalent circuits Harmonic Balance Engine, ALPAC, 3D planar electromagnetic simulator, AXIEM modeling	S-matrix S-matrix, combination of time-and-frequency domain modeling	Broader and deeper functionalities of E-CAD
3	Element representation: - active microwave elements - active MWP elements - passive elements	Multirate harmonic balance, HSPICE, Volterra, measured characteristics-based models ABSENT Lumped and distribution, microwave-band specialties	Ideal or data file-based models Rate equation-based, transmission line models Lumped, ideal	Broader and deeper functionalities of E-CAD excluding active MWP elements and modules (laser, photodiode, optical modulator)

4	Possibility for calculating the key parameters of MWP circuits and links	By one-click operation	By user-created complicated schemes	Large-signal transmission gain, Noise figure, Phase noise, Intermodulation distortion, Intercept points, etc.
5	IC Layout design and analysis	Yes	No	Broader and deeper functionalities of E-CAD for more sophisticated investigations
6	Built-in design kits from the main foundries	Yes	No	
7	Parameter optimization	Yes	No	
8	Sensitivity analysis	Yes	No	
9	Design of tolerance	Yes	No	
10	Statistical design	Yes	No	
11	Yield optimization routine	Yes	No	
12	Built-in library of producer specifics models	Yes	No	

To overcome this shortcoming, we have developed by NI AWRDE E-CAD tool a number of the models for active MWP elements, such as semiconductor laser, p-i-n photodetector, single- and multi-core optical fiber, and for rather simple MWP devices, such as optoelectronic microwave oscillator, optoelectronic microwave-frequency mixer, and optical delay lines. The results of the work are summarized in (Belkin, Golovin, Tyschuk, and Sigov 2018a; Belkin, Golovin, Tyschuk, Vasil'ev, and Sigov 2018). However, it is of considerable interest to compare the results of calculations using E-CAD and OE-CAD tools, which is presented below on the example of MP-FOL using two key active MPW elements: semiconductor laser and optical electro-absorption modulator performing E/O conversion operation (see Figure 1). The concept proposed by us consists in a comparative assessment of the quality for propagation of a digital RF signal along the same MP-FOL, in the transmission chain of which one of the tested devices is entered.

4. THE MODELS AND SETUPS FOR SIMULATION

4.1. Use of the DIL-SL

A semiconductor laser performing the function of E/O conversion is one of the most important circuit elements for both fiber optics and integrated MWP devices including the MP-FOL under research. Its important advantage in comparison with other types of optical sources is the possibility of direct modulation by RF signals, which greatly simplifies the design of the optical transmitter.

4.1.1. Modeling in VPI

Figure 2 depicts VPIphotonics Design Suite's setup of MP-FOL using a directly modulated semiconductor laser for the simulation experiments that consist of the library models of C-band DIM-SL, standard single-mode optical fiber and pin-photodiode followed by the electrical amplifier model. One can see their relevant parameters in Tables 2 and 3. To control DC bias current of a laser the setup includes the library model of DC Source. There are two instrumental modules in the setup. The first one imitates 2.5 Gbit/s, 16-QAM RF transmitter containing library models of QAM generator, output unit for power control, electrical amplifier, and a device setting the desired signal-to-noise ratio (SNR). This module generates an electrical M-QAM signal up-converted at a given RF carrier frequency of 25 GHz with a user-defined output SNR. In addition, the Electrical 16-QAM Receiver is included in Figure 2. This module detects RF signal, decodes an electrical 16-QAM signal and evaluates the error-vector magnitude (EVM) of the received QAM signal. The model of Numerical 2D Analyzer is used for two-dimensional graphical representation of the data from the QAM Receiver output.

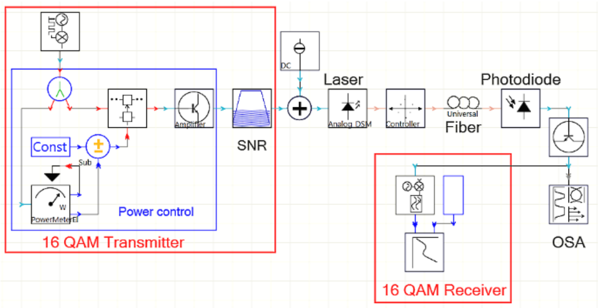

Figure 2: VPIphotonics Design Suite's setup of MP-FOL using a directly modulated semiconductor laser

4.1.2. Modeling in NI AWRDE

Figure 3 depicts NI AWRDE's setup of MP-FOL using a directly modulated semiconductor laser for the simulation experiments. The setup has the same block diagram as in Figure 2 including in-series models of 16-QAM transmitter, MP-FOL, and 16-QAM receiver, but the built-in modules are realized in a different way. In particular, the first one contains the library model of 16

QAM source, the output signal of which is up-converted on the RF carrier of 25 GHz using the models of RF tone generator and RF multiplexer. Besides, the library model of the Noise Generator to set the desired SNR is entered at its end. The second one consists of proposed early double-carrier laser model (Belkin, Golovin, Tyschuk, Vasil'ev, and Sigov 2018) including a passive sub-circuit representing frequency response of the laser under test in S2P format, library model of quasi-optical tone generator imitating laser carrier, and library model of multiplexer that performs the operation of up-converting signal to the optical range. In addition, according to the block diagram of the MP-FOL under study, the previously described (Belkin, Golovin, Tyschuk, Vasil'ev, and Sigov 2018) equivalent models of optical fiber and photodetector were introduced, followed by library models of an electric amplifier and a RF signal delay compensator. The third unit is a laboratory model of a vector signal analyzer to measure EVM values.

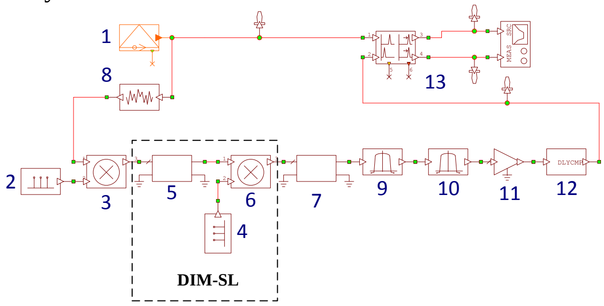

Figure 3: NI AWRDE's setup of MP-FOL using a directly modulated semiconductor laser: 1 – QAM generator; 2 – RF tone generator; 3, 6 – multiplexer; 4 – quasi-optical signal generator; 5 – frequency-modulation response block; 7 – optical frequencies splitter; 8 – RF noise generator; 9 – model of single-mode fiber as sub-circuit; 10 – model of photodetector as sub-circuit; 11 – RF amplifier; 12 – signal delay compensator; 13 – vector signal analyzer

4.2. Use of the EIM-EAM

To The operation of an electro-absorption modulator (EAM) that has recently appeared on the worldwide market is referred to the effect of increasing absorption in a quantum-size region based on quantum wells with an electric field applied. Its main advantages compared to the Mach-Zehnder modulator traditionally used for external intensity modulation of optical radiation are compactness, increased electro-optical conversion efficiency, suitability for photonic integrated circuits, and the ability to work in transceiver mode.

4.2.1. Modeling in VPI

Figure 4 depicts VPIphotonics Design Suite's setup of MP-FOL using an electro-absorption modulator (EAM) under test. The setup has the same block diagram as in Fig. 2 (see sub-section 4.1) excluding the transmitting part of MP-FOL that contains the library models of unmodulated continuous-wave laser source and EAM under test.

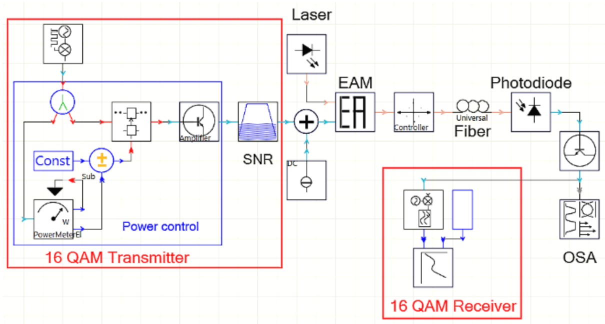

Figure 4: VPIphotonics Design Suite's setup of MP-FOL using an electro-absorption modulator

4.2.2. Modeling in NI AWRDE

Figure 5 depicts NI AWRDE's setup of MP-FOL using an externally modulated electro-absorption modulator for the simulation experiments. The setup has the same block diagram as in Fig. 4 excluding the transmitting part of MP-FOL that contains the library model of quasi-optical tone generator imitating laser carrier, the library model of multiplexer that performs the operation of up-converting signal to the optical range, and a passive sub-circuit representing frequency response of the EAM under test in S2P format. Notice that earlier, we proposed and described in detail (Belkin, Golovin, Tyschuk, and Sigov 2018b) a non-structural nonlinear model of the EAM suitable for developers of local telecommunication systems based on RoF technology. However, its simplified model is used here.

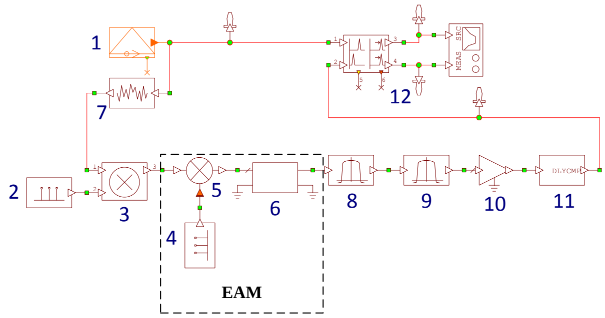

Figure 5: NI AWRDE's setup of MP-FOL using an electro-absorption modulator: 1 – QAM generator; 2 – RF tone generator; 3 – multiplexer; 4 – quasi-optical signal generator; 5 – behavioral mixer; 6 – optical frequencies splitter; 7 – RF noise generator; 8 – model of single-mode fiber as sub-circuit; 9 - model of photodetector as sub-circuit; 10 – RF amplifier; 11 – signal delay compensator; 12 – vector signal analyzer

5. SIMULATION EXPERIMENTS

5.1. Reference Data

In this work, the subject of the study is a microwave-photonics fiber-optic link (MP-FOL); the devices of study are directly modulated semiconductor laser, an electro-absorption modulator for external modulation, and standard single-mode fiber (SMF). The tools for the computer simulation are two well-known commercial program environments such as OE-CAD VPIPhotonics

Design Suite™ and E-CAD NI AWRDE. The study took into account two key distortion sources of the transmitted signal: a chirp of laser and modulator as well as losses and chromatic dispersion of the fiber. To eliminate the influence of nonlinear effects during modulation and signal transmission through the fiber, RF and optical signal levels were selected so that the modulation index did not exceed 30%, and the optical power in the fiber was not more than 5 mW. Table 2 lists the common reference data for the MP-FOL under study. In addition, Table 3 and 4 list the reference data for the DIM-SL and EIM-EAM, correspondingly.

Table 2: Common Reference Data for the MP-FOL under Study

Parameter		Value
Length of pseudo-random bit sequence		2^{15}-1
Bitrate		2.5 Gbit/s
RF Carrier Frequency		25 GHz
Input RF Power		-11 …-26 dBm
Type of RF modulation		16-QAM
Optical Carrier		C-band (1552.52 nm)
Type of optical modulation		Intensity
PIN-Photodiode	Responsivity	0.92 A/W
	Dark current	100 nA
	3dB Bandwidth	20 GHz
	Optical Input Power	<3 mW
Post-amplifier	Gain	40 dB
	Noise Spectral Density	$20\cdot10^{-12}$ $A/Hz^{1/2}$
Optical Fiber	Type	SMF-28e+
	Length	up to 20 km
	Attenuation	0.2 dB/km
	Dispersion	$17e^{-6}$ s/m^2
	Dispersion Slope	80 s/m^3

Table 3: Reference Data for Direct Intensity Modulated Semiconductor Laser

Parameter	Value
Operating current	50 mA
Linewidth	500 kHz
Relative intensity noise	-160 dB/Hz
Threshold current	10 mA
Slope efficiency	0.14 W/A
Linewidth enhancement factor (α)	4.6
Adiabatic chirp factor (*k*)	3.2 GHz/mW

Table 4: Reference Data for External Intensity Modulated Electro-Absorption Modulator

Parameter	Value
Operating voltage	-0.5 V
Extinction ratio	14 dB
Slope efficiency	0.14 W/V
Linewidth enhancement factor (α)	1.0
Adiabatic chirp factor	0

5.2. Simulation results

In preparation for the simulation experiments, the modulation index of each device under study was optimized in such a way as to ensure the maximum output RF carrier-to-noise ratio while maintaining the low-signal mode at the modulating frequency. . Figures 6, 7 depict examples of simulating EVM vs fiber length characteristics for the devices under study during transmission of 2.5 Gbit/s, 16-QAM RF signal at the frequency of 25 GHz using RF signal-to-noise ratio (SNR) of 50 and 25 dB. For the best vision, there are the insets in the Figures showing constellation diagrams at fiber length of 10 km. In addition, in the Figures, the dotted lines indicate the standard limit of the EVM during transmission of the 16-QAM signal, which is 12.5% (ETSI 2017).

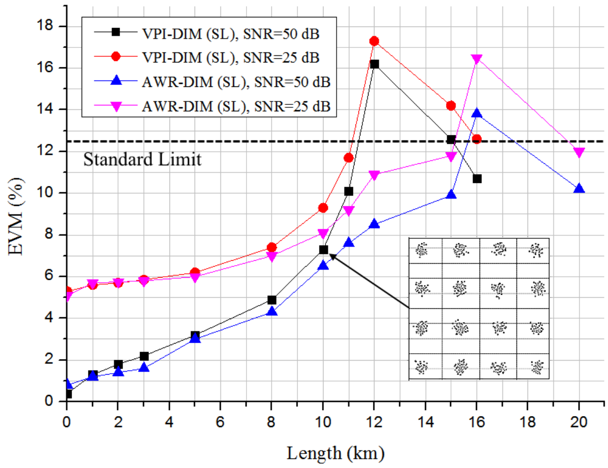

Figure 6: EVM vs fiber length characteristics based on MP-FOL simulation including DIM-SL

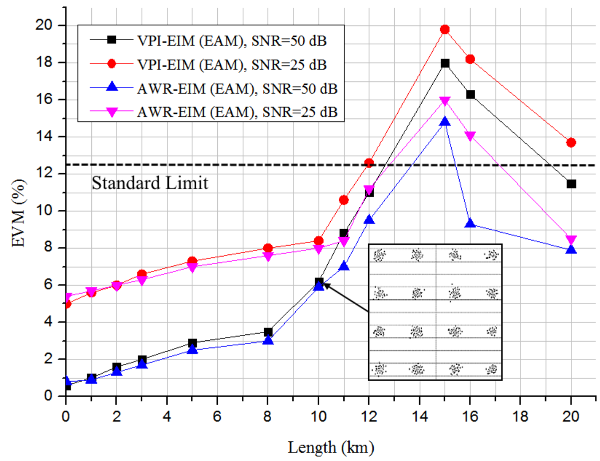

Figure 7: EVM vs fiber length characteristics based on MP-FOL simulation including EIM-EAM

The following outputs can be derived from our study:

- the EVM vs fiber length characteristics simulated by the both software closely coincide with each other at the signal-to-noise ratio of 50 and 25 dB within the FOL distance of up to 10 km;
- for longer FOL lengths, all characteristics show a peak that exceeds the standard limit, caused by the effect

of dispersion in the fiber (Urick 2015). Figure 8 exemplifies the photodiode's output spectrum explaining the dispersion effect, which is remarkably reduces SNR and therefore increases EVM value. To eliminate it in order to increase the length of the FOL, it is required to introduce at its end a dispersion corrector, which is a standard element in fiber-optic communication systems;

- the fiber distance for the FOL under study including a directly modulated semiconductor laser reaches within standard limit of 12.5% up to 11 km for VPI simulation and up to 15 km for AWRDE simulation ;
- the fiber distance for the FOL under study including a externally modulated electro-absorption reaches within standard limit of 12.5% up to 12-14 km for the simulations by the both software tools;
- The most likely reason for this behavior is the effect of an electro-optical converter chirp, which is much greater with a laser than with a modulator (see α- and k-factors in Tables 3 and 4). However, this parameter is not included in the proposed AWRDE's laser and modulator models.

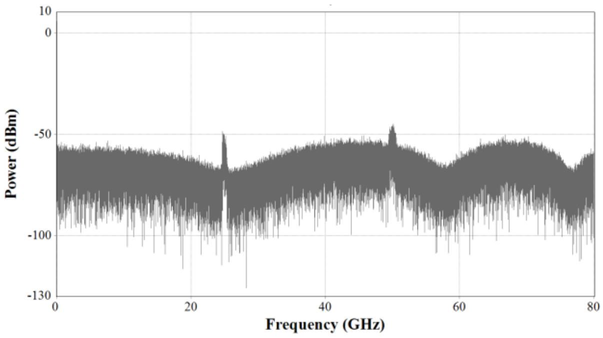

Figure 8. Photodiode's output spectrum explaining the dispersion effect

CONCLUSION

In the paper, we compared two off-the-shelf computer-aided design software: VPIphotonics Design Suite for the simulation of photonics circuits and NI AWRDE for the simulation of microwave-electronics circuits on the example of a microwave-photonics-based fiber-optics link using two key active microwave-bandwidth optoelectronic devices: semiconductor laser or optical electro-absorption modulator performing electro-optic conversion operation. The concept proposed consists in a comparative assessment of the quality for propagation of a digital radio-frequency signal along the same fiber-optics link, in the transmission chain of which one of the tested devices is entered. The result was a relatively close coincidence for the quality of digital radio signal transmission, which indicates the possibility of modeling in any of the software environments. Therefore, the designer depending on the requirements for the fiber-optics link being developed should make the choice of suitable software. In this case, the absence of library models of optical and optoelectronic devices in the NI AWRDE program's current version should be taken into account. Nevertheless, the problem is simplified due to the possibility of using the previously developed models of these devices in the form of sub-circuits.

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