AN ADVANCED APPROACH TO SIMULATION OF SUPER-WIDE BANDWIDTH INFORMATION AND COMMUNICATION SYSTEMS COMBINING MICROWAVE AND PHOTONIC INDUSTRIAL TECHNOLOGIES

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ABSTRACT

A novel approach to simulation and design of combined information and communication systems based on microwave and photonic industrial technologies using high-power commercial microwave electronic CAD tool is proposed. A detailed validation of this approach based on the results of E-CAD simulation and experimental verification of a photonic beam former is presented as well.

Keywords: phased array antenna, photonic beamformer, electronic computer-aided design tool.

Microwave photonics (MWP) is an interdisciplinary scientific and technological field that combines the domains of microwave and RF engineering and photonics (Urick Jr., McKinney, and Williams 2015). This field in the last 30 years has attracted immense interest and generated many new R&Ds from both the scientific community and the commercial sector. Emerging applications for radio-over-fiber (RoF) hybrid communication systems, sub-terahertz wireless systems, radar, and electronic warfare systems indicate that MWP is set to be a subject of increasing importance. Generally, MWP devices are the examples of an intimate integration of photonics, microwave electronics, and planar antenna technologies for producing a complicated functional module in a multichannel analog environment. In particular, MWP technology opens the way to super-wide bandwidth transmitting characteristics at lower size, weight, and power as compared with traditional electronic information and communication systems (Paolella, DeSalvo, Middleton, and Logan 2015). For example, in a typical arrangement of MWP-based software defined RF receiver, a photonic circuit is inserted between two microwave electronic chains (Fig. 1). For direct and inverse transformations of microwave and optical signals there are two interface units at its bounds: electrical-to-optical and optical-to-electrical converters. Between the interfaces there are various photonics processing units for transmission, switching, distribution, filtration, and frequency conversion of microwave signals in optical domain.

1. THE KEY MICROWAVE PHOTONICS ELEMENTS

There are 5 basic MWP types of active optoelectronic devices which are depicted in Fig. 2:

- optical-electric converter (Fig. 2, a), for example, photodiode;
- electric-optical converter (Fig. 2, b), for example, semiconductor laser;
- optically controlled microwave sensor (Fig. 2, c), for example, microwave generator which parameters (frequency, output power) depend on optical signal;
- converter of optical signal (Fig. 2, d), for example, optical modulator, laser amplifier;
- converter of microwave signal (Fig. 2, e), for example, microwave amplifier which gain is controlled by an optical signal, optoelectronic delay line.

Common distinctive feature of all above-mentioned devices and functional elements is their C- (1530…1565 nm) and/or L- (1565…1625 nm) operational spectral ranges, as specified in ITU-T. The main reasons for such a choice are the lowest losses in silica fiber, the widest operation spectral range and availability of low cost and high performance fiber amplifiers for compensation of losses.

In addition to above listed 5 types of optoelectronic devices, there are 2 types of devices based on all-optical interaction, that can be effectively applied in microwave photonics equipment:

- optically pumped converter of optical signals (Fig. 2, e), for example, Erbium, Raman and Brillouin fiber amplifiers;
- optically pumped sensor of optical signal (Fig. 2, g), for example, the Erbium fiber oscillator.

These elements and devices represent the principal building blocks for creation of essentially newer

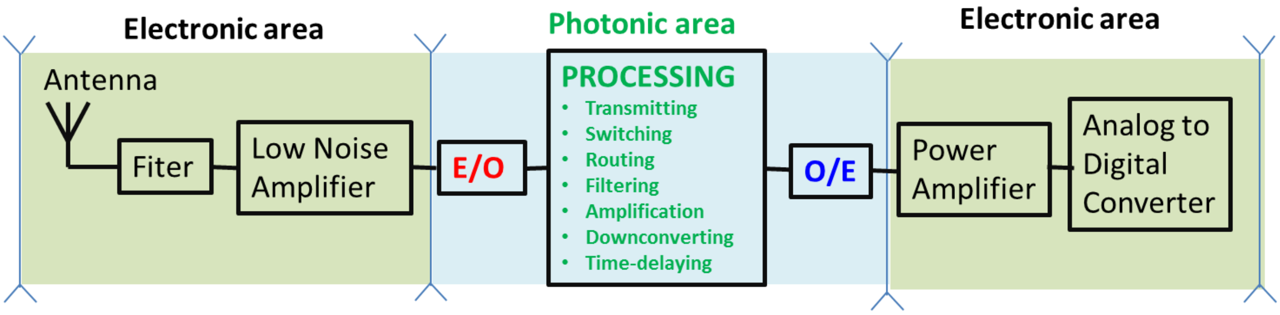


Figure 1: A typical arrangement of MWP-based software defined RF receiver

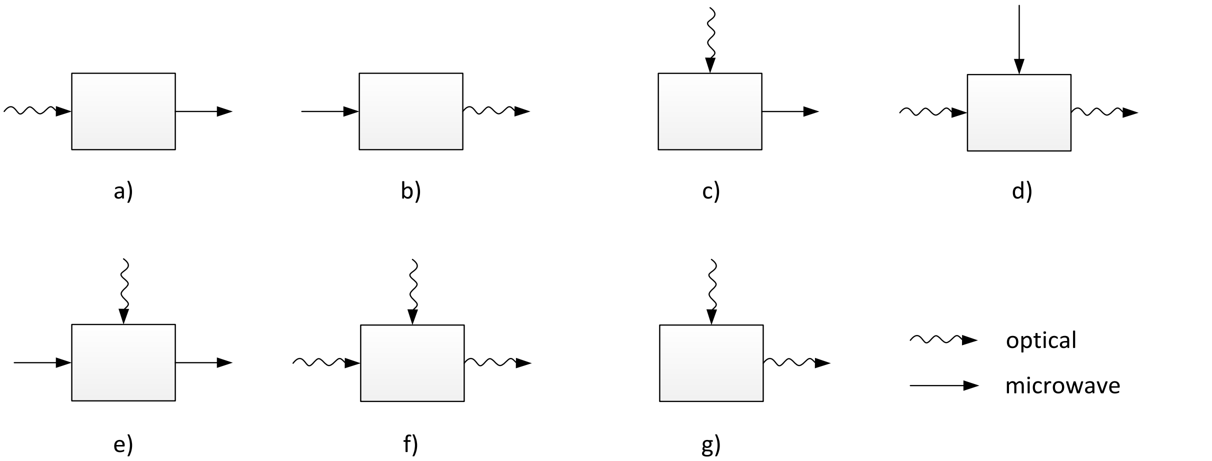


Figure 2: The classification of active optoelectronic devices and functional elements for microwave photonics technology

devices, which can significantly improve the key technical and economic characteristics of modern information and communication systems such as speed, operating frequency band, dynamic range, electromagnetic compatibility, etc.

2. SELECTION OF AN OPTIMAL PRODUCT FOR COMPUTER DESIGN

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 (CAD) tools because the existing optical and optoelectronic CAD tools (OE-CAD) are not as developed as compared with the CAD tools intended for modeling of microwave devices (E-CAD) (Leijtens, Lourec, and Smit 1996). Increasing the accuracy of photonic circuits taking into account influence of their parasitic parameters in microwave band requires the use of the high-power microwave E-CAD tool (Leijtens, Lourec, and Smit 1996) working at symbolical level.
Table I lists detailed comparison of typical modern OE-CAD tool VPI Transmission Maker of VPI Photonics and well-known E-CAD tool AWRDE of National Instruments. Recently, we have developed by NI AWRDE E-CAD tool a number of models for active optoelectronic elements, such as semiconductor laser (Belkin, et all 2011; Belkin and Iakovlev 2015), p-i-n photodetector (Belkin and Sigov 2015) and for rather simple microwave photonics devices, such as optoelectronic microwave oscillator (Belkin and Golovin 2015)(Belkin and Golovin 2015) and optoelectronic microwave frequency mixer (Belkin and Tyschuk 2015). Below we present the results of E-CAD simulation and experimental verification for a complex device such as photonic beam former of a super-wide bandwidth microwave phased array antenna (PAA).

3. MODELING OF SUPER-WIDE BANDWIDTH MICROWAVE PHOTONICS-BASED BEAM FORMER

So far, there are two approaches for the beam steering in modern microwave-band PAAs: using phase shifters or delay lines. The first one has simplest architecture but it has difficulties to achieve a wide scanning angle in super-wide bandwidth and suffers from so-called beam squint distortion. In order to achieve wide angle scanning of PAAs, the developer must implement real time delay lines based on so-called true time delay (TTD) approach (Mailloux 2005) to substitute the traditional phase shifters. Conventional TTD is composed of waveguide or coaxial cable, which has high loss of signal and engineering complexity. Application of microwave photonics and fiber technologies to PAA can reduce transit time and aperture effect, and resolve the problem of wide angle and wide bandwidth scanning (Yao 2009).
Let us compare the above beam former architectures for microwave photonics-based PAA. To be specific, the calculations were performed for the 16-element PAA.

Table I: Comparison of modern E-CAD and OE-CAD tools

#	Feature	Realization		Comments
		By E-CAD (NI AWRDE)	By OE-CAD (VPI Photonics)	
1	Analysis approach	Building Blocks, 3D electromagnetic analysis	Building Blocks,	
2	Simulation methods			
	- Linear circuits	S-,Y- matrix, equivalent circuits	S-matrix	
	- Nonlinear circuits	Harmonic Balance Engine ALPAC, 3D planar electromagnetic simulator AXIEM modeling	S-matrix, combination of time-and-frequency domain modeling	
3	Element representation			
	-active microwave elements	Multirate harmonic balance, HSPICE, Volterra, based on measured characteristics models	Ideal or based on measured characteristics models	
	- active MWP elements	Absent	Rate equation-based, transmission line models	
	- passive elements	Lumped and distribution, microwave-band specialties	Lumped, ideal	Waveguides, couplers, resonators, resistors, capacitor, inductor
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, so on
5	IC Layout design and analysis	Yes	No	
6	Built-in design kits from the main foundries	Yes	No	
7	Parameter optimization	Yes	No	For more sophisticated investigations
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 specific models	Yes	No	

3.1. Phase shifter-based photonic beam former
To evaluate phase shifter-based photonic beam former performances an equivalent circuit including the models of previously studied microwave photonics component and built-in AWRDE's library models was developed. The simulation was performed by calculating the PAA's normalized radiation patterns (NRP) in the frequency band of 6-18 GHz. Fig. 3 shows examples of the calculation of the NRPs for the case of discrete phase delay selected in the center of the frequency band. As can be seen from the Figure, when a discrete phase shift $\Delta\varphi = 13°$ at the extreme frequencies of the band, there are significant errors $\delta\theta = 20°$ at the frequency of 6 GHz and $\delta\theta = 7°$ at a frequency of 18 GHz. From the Figure, one can make an unambiguous conclusion: to achieve acceptable error value the instantaneous band of RF signal must be narrower.

4. TTD-BASED PHOTONIC BEAM FORMER USING SWITCHABLE DELAY LINES

As described above, the main advantage of this arrangement is in the relative simplicity and straightforward implementation, as the scheme is a complete "optical" analogue of a standard microwave PAA scheme. To evaluate its characteristics an equivalent circuit including the models of previously studied microwave photonics components and built-in AWRDE's library models was developed too. Modelling was also conducted by calculating the PAA's NRP in the frequency band 6-18 GHz.

Figure 4 shows an example of calculation of the NRP in the upper frequency of the band for the photonic beam former based on switchable optical delay line with 3-ps increments. As one can see from the Figure, the photonic beam former investigated in this section is provided by a uniform spatial shift of the main lobe that is more than 40°. The same was observed on other frequencies of the band.

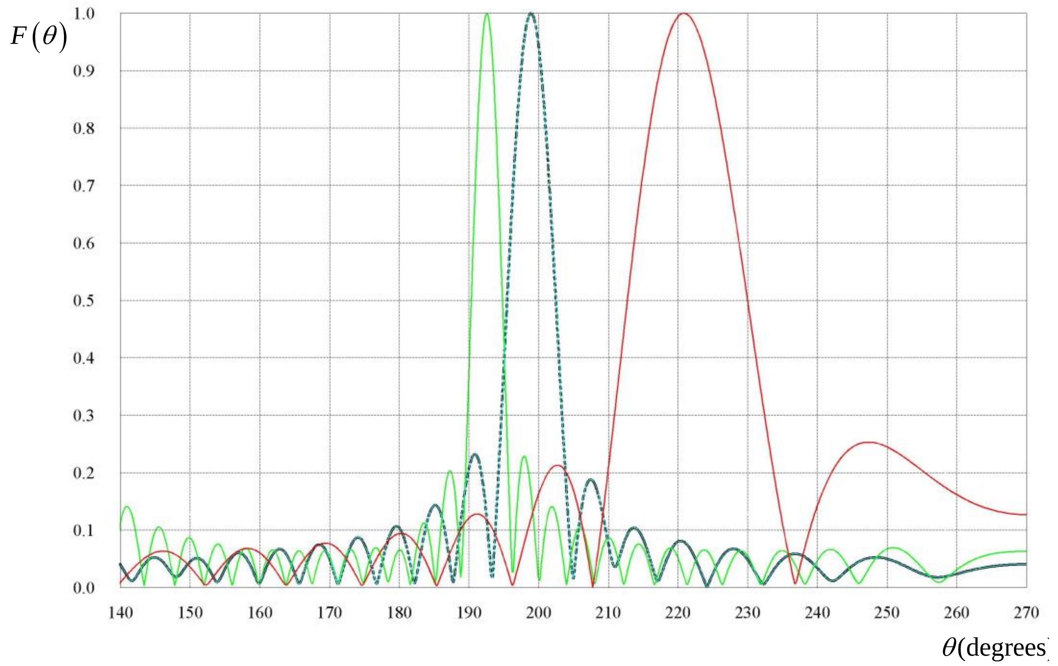


Fig. 3. Microwave photonics PAA's normalized radiation patterns at central frequencies of 6 GHz (right), 12 GHz (middle), and 18 GHz (left)

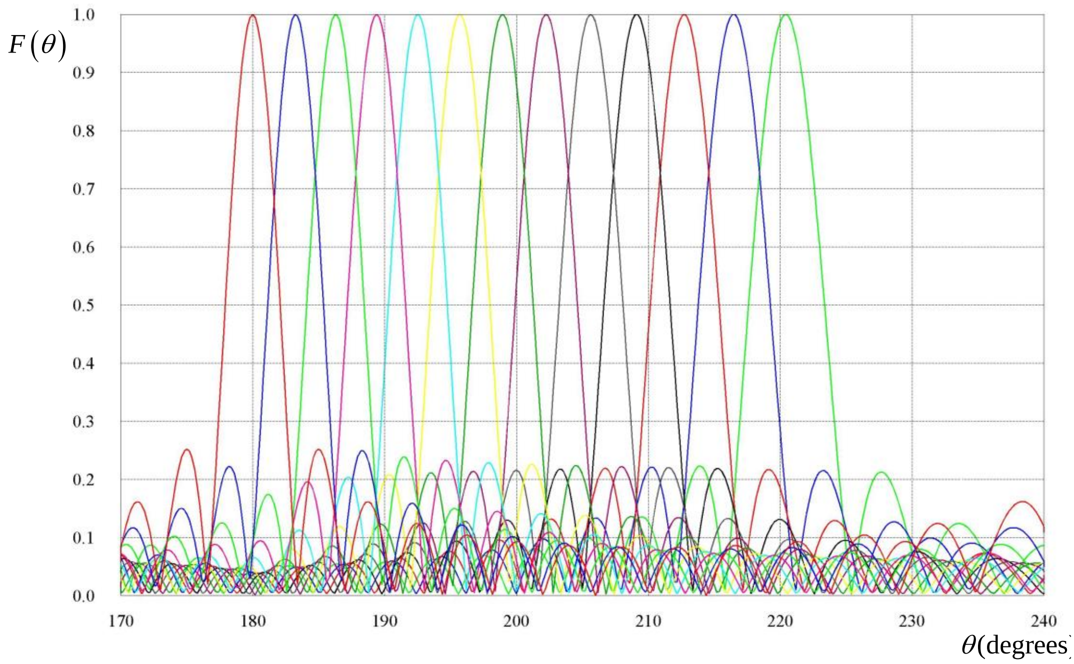


Fig. 4. Microwave photonics PAA's normalized radiation patterns at the frequency 18 GHz for photonic beam former using switchable delay lines

4.1. Super-wide bandwidth photonic beam former combining switchable delay lines and multichannel Bragg grating

The key advantage of the building principle proposed in (Pham, Arokiaswami, and Desmond 2008) is in efficiency when used in multi-element PAA. The results of its simulation and experimental verification are described in more details below.

The model of photonic beam former, implemented in AWRDE CAD's Schematic environment, which combining switchable optical delay lines and multichannel Bragg grating (Figure 5) includes:

- section of semiconductor lasers and spectral multiplexer;
- section of single sideband external modulation including two electro-optic Mach-Zehnder modulators;
- four-channel Bragg grating;
- section of the optical amplifier;
- optical distribution section (ODS), which forms 16 optical channels with preset values of the delay time;
- section of photodetector, which provides detection of 16 RF signals with the set time delays.

For simulation and experimental verification for the circuit of Fig. 5 the following reference data were taken: Operating frequency band of PAA is 1-18 GHz; The antenna array has 16 non-directional antennas spaced at $0{,}5\lambda_{min}$ (corresponding to the maximum operating frequency of 18 GHz). Simulation and experiment are carried out for 2 cases:

1) at a fixed microwave frequency 10 GHz when the delay time Δt = 1, 5, 10 and 15 ps;
2) at a fixed time delay Δt = 15 ps when operating frequencies F= 6, 12 and 18 GHz.

Figure 6 depicts the results of calculations (dashed curves) and experiments (solid curve) of NRPs at various time delays. Besides, Figure 7 depicts the results of calculation (dashed curve) and experiment (solid curve) of NRPs at the operating frequencies of 6, 12 and 18 GHz when time delay is fixed on 15 ps. As follows from the Figures, there is a close agreement between the calculated and experimental data, due to the high accuracy of the built library models of AWRDE tool, as well as due to the fact that our models of optoelectronic components are based on their experimentally measured parameters.

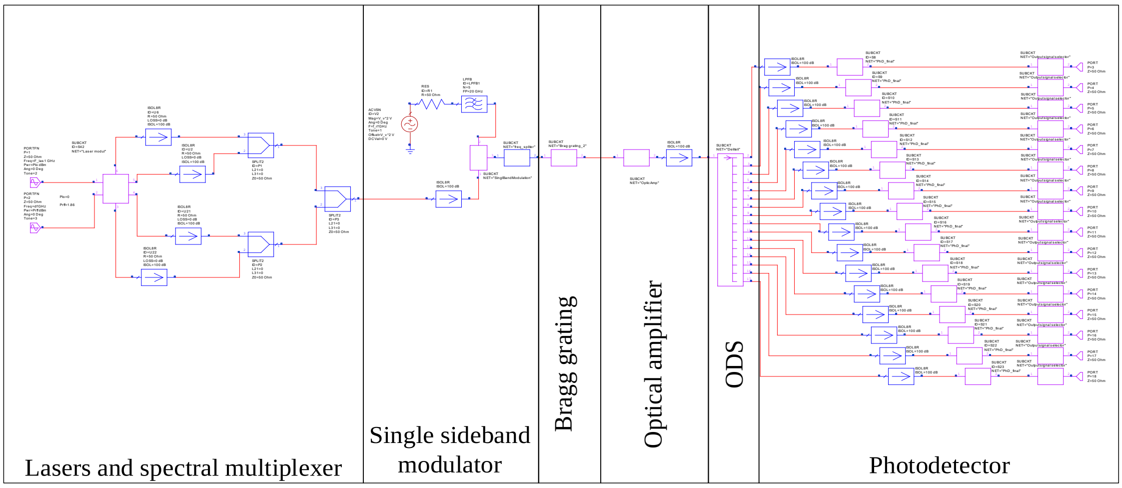
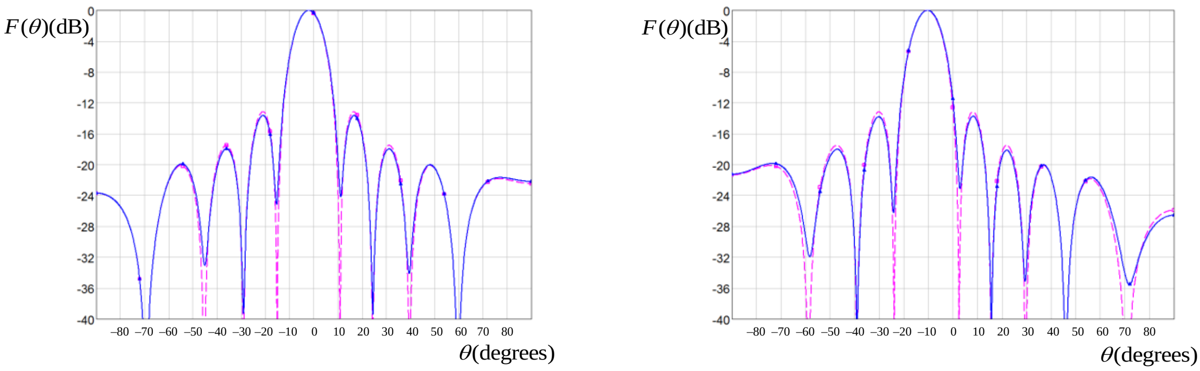
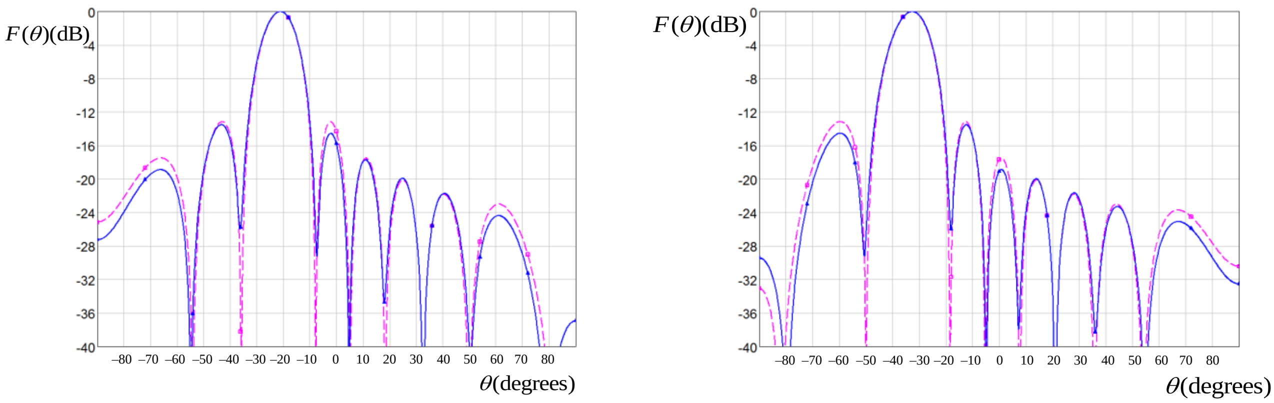


Fig. 5. Equivalent circuit of super-wide bandwidth photonic beam former combining switchable delay lines and multichannel Bragg grating

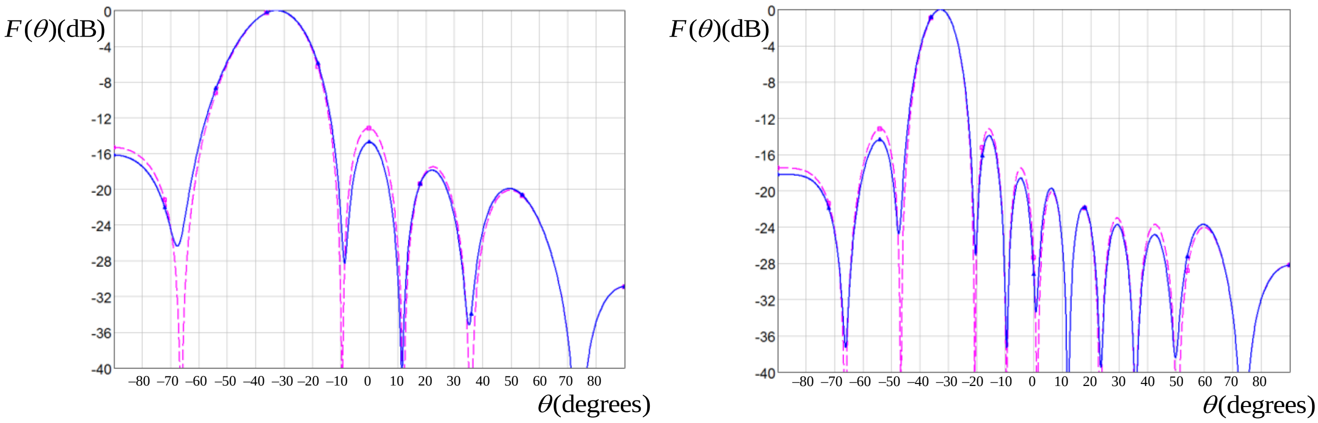


a) b)



c) d)

Fig. 6. Calculated (dashed curve) and measured (solid curve) NRPs of microwave photonics PAA at 10 GHz: a - Δt = 1 ps (offset of the main lobe Δθ = -2.2°); b - Δt = 5 ps (offset of the main lobe Δθ = -10.4°); c - Δt = 10 ps (offset of the main lobe Δθ = -21.3°); d - Δt = 15 ps (offset of the main lobe Δθ = -32.9°)



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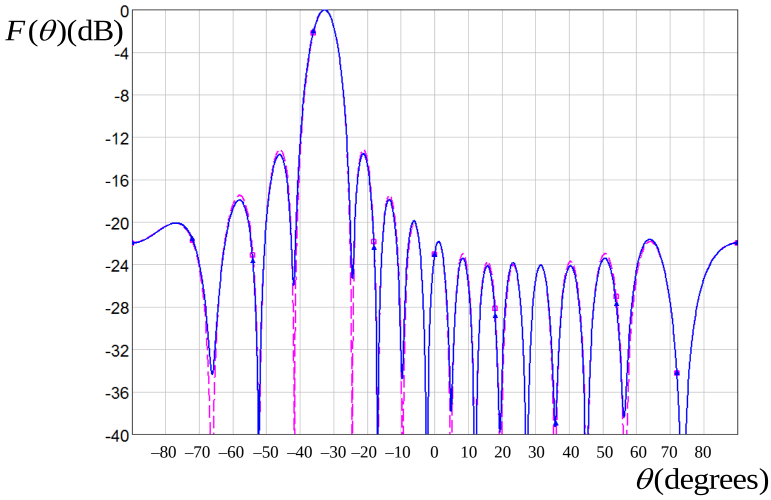

c)

Fig. 7. Calculated (dashed curve) and measured (solid curve) NRPs of microwave photonics PAA at time delay of 15 ps when operating frequency is 6 GHz (a), 12 GHz (b), and 18 GHz (c)

5. CONCLUSION

We have presented the results of design, simulation and testing of super-wide bandwidth photonic beam former for microwave photonics phased array antenna as a complex example of combined information and communication systems based on microwave and photonic industrial technologies using high-power commercial microwave electronic CAD tool. The good fit of the calculated and experimental data is achieved due to the high accuracy of the built library models of AWRDE tool, as well as due to the fact that our models of optoelectronic components are based on their experimentally measured parameters.

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