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Comparison of RF Photonics-Based Beamformers for Super-Wide Bandwidth Phased Array Antennas

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Abstract. We demonstrate the NI AWRDE E-CAD tool-based simulation experiments to compare the three arrangements of photonic beam forming networks. The results confirm clearly the benefits of the proposed arrangement based on combination of multichannel fiber Bragg grating and switchable optical delay lines providing super-wide operating bandwidth and the better economical characteristics of microwave-band phased array antennas.

1. INTRODUCTION

As well known, antenna represents a basic unit of any on-air radio frequency (RF) system defining its communication range and fidelity. Nowadays, its exploitation in the communication and radar means as a phased array antenna (PAA) [1] results in remarkably increased footprint and operation flexibility thanks to electronic beam steering function that is fulfilled by a beam forming network (BFN). For modern communication and radar application [2] an extremely broad instantaneous bandwidth is required, so super broadband phase shifting or time shifting techniques must be utilized. On this way, RF and microwave photonics is a very attractive technology for PAA's BFN realization due to its super-wide operating bandwidth, immunity to electromagnetic interference, lightweight, and flexible system implementation [3]. So over the past years, a lot of RF photonic-based BFN architectures have been proposed including both phase shifting and time shifting techniques.

In process of R&Ds of such combined PAA including microwave and photonic units there was an issue which a computation technique is desired for their optimal modeling, analysis, and design. The essence is that for the accurate simulation of such complicated systems it is necessary to pay remarkable attention to their functioning in both spectral ranges. Now for the solution of this task, the approach referred to several computer-aided design (CAD) tools is in common use, because the existing optical and optoelectronic CAD tools (OE-CAD) are developed much weaker, than the CAD tools intended for modeling of microwave devices (E-CAD) [4]. In this regard, the conclusion has been drawn that the optimal way for increasing the accuracy of photonic circuits taking into account influence of their parasitic parameters in microwave band requires use of the high-power microwave E-CAD tool [5] working at symbolical level. Following the approach, we have developed by NI AWRDE computer tool a number of models for active optoelectronic elements, such as semiconductor laser [6, 7], p-i-n photodetector (PD) [8] and Mach-Zehnder modulator (MZM) [9].

Proceeding the works, in this paper the results of NI AWRDE-based simulation experiments to compare

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the three versions of photonic BFN arrangements using photonic phase shifters, switchable optical delay lines, and our new arrangement based on a combination of multichannel fiber Bragg grating (FBG) and switchable optical delay lines are demonstrated.

2. BEAM FORMING NETWORK ARRANGEMENTS

Fig. 1,a shows the first photonic BFN arrangement for comparison that is a part of 16-element PAA transmitting channel. In this case, RF signals are converted by a laser to optical range and shared into 16 branches by optical coupler. Each branch consists of a tunable photonic phase shifter (P-PS), photodetector (PD), and antenna element. In the process of simulation experiment we used AWRDE equivalent circuit model including the model of directly modulated semiconductor laser [6], library coupler model of 1:16, the previously developed P-PS model [9], the model of PD [8], and ideal isotropic antenna model.

Fig. 1,b shows the second photonic BFN arrangement for comparison that is a part of 16-element PAA transmitting channel. In this case, 16 unmodulated lasers of different wavelengths λ1- λ16 are used. The part of the same RF signal is converted by corresponding Mach-Zehnder modulator (MZM) to optical range and shared into 16 branches by optical coupler. Each branch consists of a switchable optical delay lines (ODL). Then the delayed optical signals are converted into RF band by PD and emitted by antenna element. In the process of simulation experiment we used AWRDE equivalent circuit model including the model of continuous wave (CW) semiconductor laser [7], previously developed MZM model [9], library models of 1:16 couplers, switch, delay line, as such as the model of PD [8].

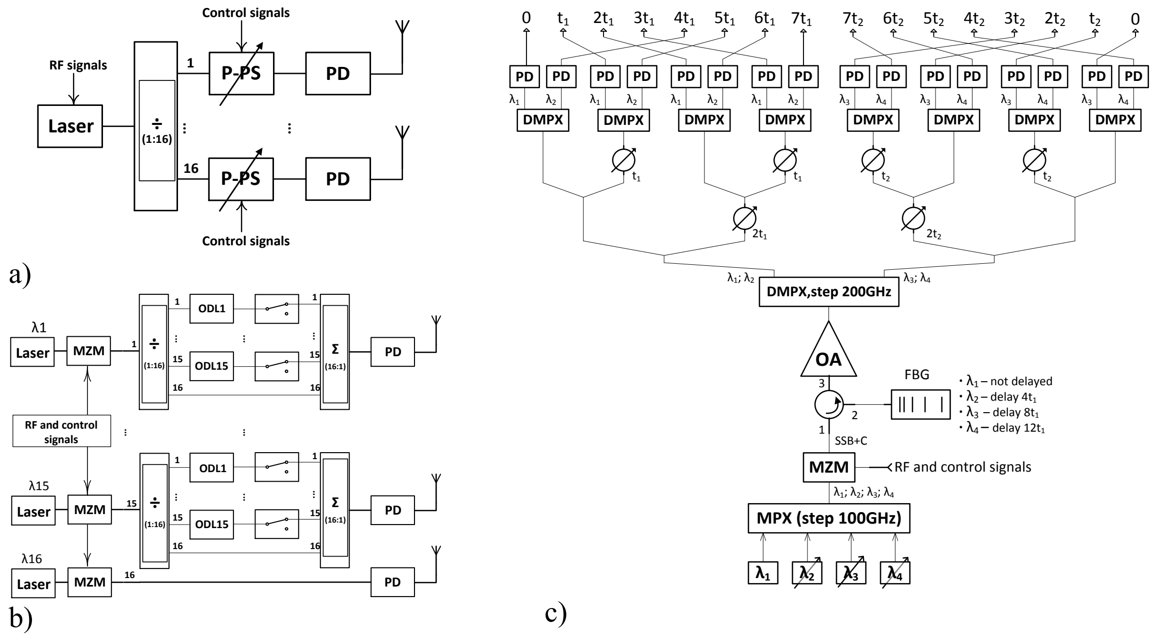


Fig. 1. 16-element RF photonic BFN based on photonic phase shifters (a), 16-element RF photonic BFN based on switchable optical delay lines (b) and 16-element RF photonic BFN based on a combination of multichannel fiber Bragg grating and switchable optical delay lines (c)

Fig. 1,c shows the third photonic BFN arrangement for comparison that is a part of 16-element PAA transmitting channel too. In this case, only 4 lasers of different wavelengths λ1- λ4 (3 tunable and 1 untuned) are used. Laser emissions are summarized in a spectral multiplexer (MPX), modulated in a common MZM by RF signal, and through optical circulator are input to 4-channel reflected FBG. The levels of corresponding delayed signals are recovered by an optical amplifier (OA), pairwise branched out, delayed once more by corresponding switchable ODL, branched out again by spectral demultiplexers (DMPX), converted into RF band by PDs and emitted by antenna elements.

3. NI AWRDE TOOL-BASED SIMULATION EXPERIMENTS

To evaluate phase shifter-based photonic beam former (Fig. 1,a) performances an equivalent circuit including the models of previously proposed microwave photonics components 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 using the well-known formulas [1]. Fig.2 shows examples of the calculation of the NRPs for the case of discrete phase delay selected in the center of a 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 $\delta\theta = 22°$ 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. As described above, the main advantage of the arrangement of Fig. 1,b 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. Modelling was also conducted by calculating the PAA's NRP in the frequency band 6-18 GHz. Fig. 3 depicts an example of calculation of the NRP in the upper frequency of the band for the photonic BFN based on switchable optical delay line with 3-ps increments. As one can see from the Figure, the photonic BFN 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.

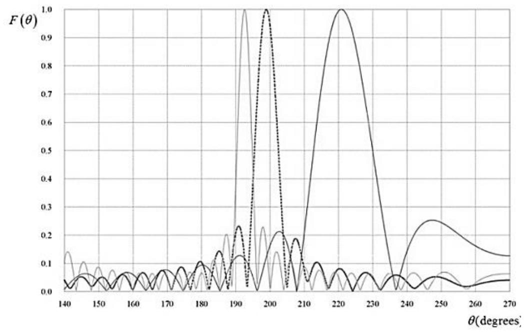


Fig. 2 Microwave photonics PAA NRPs at central frequencies of 6 GHz (right), 12 GHz (middle), and 18 GHz (left)

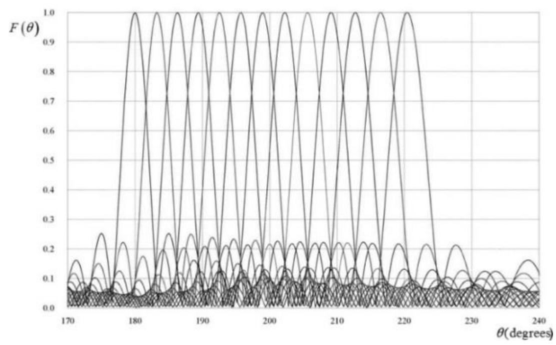


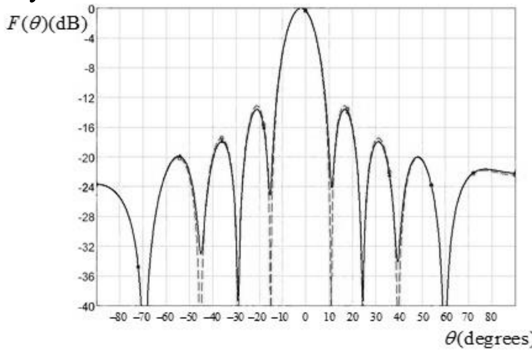
Fig. 3. Microwave photonics PAA NRPs at the frequency 18 GHz for photonic beam former using switchable delay lines

For simulating photonic beam former based on combining switchable delay lines and multichannel Bragg grating in two exiting modes of antenna elements the following reference data were taken: operating frequency band of PAA is 6-18 GHz; the antenna array has 16 non-directional antennas spaced at $0{,}5\lambda_{min}$ (corresponding to the maximum operating frequency of 18 GHz). Simulations are carried out for 2 cases: 1) at fixed microwave frequency 10 GHz when the delay time Δt = 1, 5, 10 and 15 ps; 2) at fixed time delay Δt = 15 ps when operating frequencies F= 6, 12 and 18 GHz.

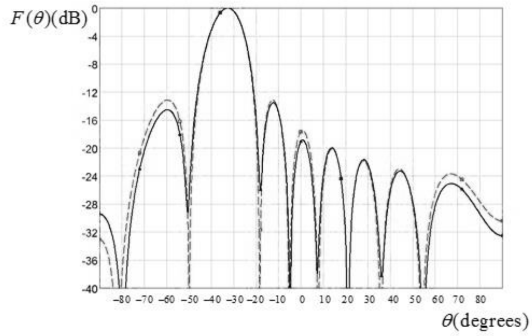
The simulation results depict in Fig. 4 and Fig. 5, correspondingly. For comparison the same plots show the calculation results of ideal NRPs (point curves) [1]. The close coincidence proves the correctness of the proposed model. A clear output from the Figures is that the position of main lobe is unchanged, i.e. RF photonics-based beam former arrangement of Fig. 1,c is usable for super-wide bandwidth phased array antennas.

CONCLUSION

The comparison of the simulation results showed that the arrangement of Fig. 1,a, despite the greatest simplicity had a relative narrow instantaneous bandwidth (up to 300MHz) and so was unpractical for super wideband PAAs. The both residuary arrangements due to use so called true-time delay (TTD) technique [10] equally suit for precision high-speed steering of antenna beam in the band of 1-18 GHz with instantaneous bandwidth up to 5 GHz but the main benefit of Fig. 1,c's arrangement is in simplicity and scalability. The last features one can clearly see from the Figs: for the realization of 16-channel BFN in the arrangement of Fig. 1,b as much as 16 lasers, 16 optical modulators, and 240 optical delay lines must be used. On the other hand, for the arrangement of Fig. 1,c only 4 lasers, one modulator, and 6 delay lines are needed.

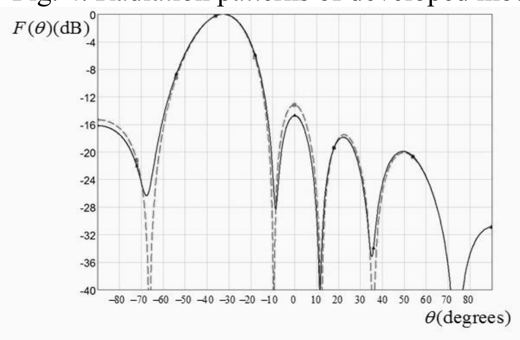


a)

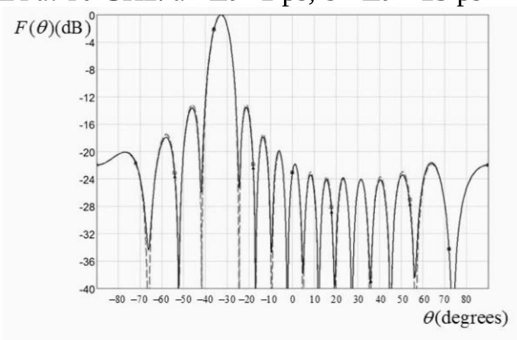


b)

Fig. 4. Radiation patterns of developed model of PAA at 10 GHz: a - Δt =1 ps; b - Δt = 15 ps



a)



b)

Fig. 5. Radiation patterns of developed model of PAA at Δt = 15 ps: a - F = 6 GHz; b - F = 18 GHz

REFERENCES

[1] Mailloux R 2005 Phased Array Antenna Handbook *Artech House* p 496
[2] Bradsell P 1990 Phased arrays in radar *Electron. Commun. Eng. J.* pp 45-51
[3] Matthews P 1999 Practical photonic beamforming *Proc. IEEE Int. Topical Meeting on Microwave Photonics* pp 271-274
[4] Belkin M 2012 Multiscale Computer Aided Design of Microwave-Band P-I-N Photodetectors, pp. 231-250. *In book "Photodetectors" Ed. By S. Gateva – InTech, Chapter 6*
[5] Leijtens X, Le Lourec P, Smit M 1996 S-Matrix Oriented CAD-Tool for Simulating Complex Integrated Optical Circuits *IEEE J. of Selected Topics in Quantum Electronics* pp 257-262
[6] Belkin M, Belkin L, Sigov A, Iakovlev V, Suruceanu G, Kapon E 2011 Performances of Microwave-Band Analog Signal Transmission using Wafer-Fused Long Wavelength VCSELs *IEEE Phot. Technol. Lett.* pp 1463-1465
[7] Belkin M, Iakovlev V 2015 Microwave-band Circuit-level Semiconductor Laser Modeling *Proc. 9th European Modelling Symposium on Mathematical Modelling and Computer Simulation EMS2015* (Madrid Spain) pp 1-3
[8] Belkin M, Sigov A 2015 Circuit-Level Large-Signal Modeling of Microwave Bandwidth Photodetector *Proc. International Conference on Electromagnetics in Advanced Applications, ICEAA 2015* (Italy) pp 1587–1589
[9] Belkin M, Golovin V, Tyschuk Y 2016 The equivalent electrical model of the Mach-Zehnder electro-optical modulator at the CAD AWR Microwave Office *Proc. International Conference "Microwave & Telecommunication Technology" (CriMiCo'2016)* pp 2353 — 2359 (in Russian)
[10] Shaw A and Wilkins N 2010 Frequency Invariant Electro-Magnetic Source Location Using True Time Delay Beam Space Processing Proc *IEEE Intl. Symposium on Phased Array Systems and Technology*