Using of microwave photonic transversal filter for broadband signal direction estimation in microwave photonic beamforming system for linear phased array antennas

S I Ivanov, A P Lavrov and I I Saenko

Peter the Great St. Petersburg Polytechnic University, 29 Polytechnicheskaya str., St. Petersburg, 195251, Russia

E-mail: lavrov_ap@spbstu.ru

Abstract. An approach is considered to estimate direction of arrival of broadband microwave signals in linear phased array antenna with photonic beamforming system by using additional subsystem – microwave photonic filter. The frequencies of the notches in the spectrum of broadband signal at the microwave photonic transversal filter output allow to measure mutual delay between signals from two antenna array elements, and thus providing estimation of the signal arrival angle. Architecture of the constructed transversal filter is based on the components of two analog fiber-optic links being a part of antenna array photonic beamforming system. Some shown results of test measurements of microwave photonic transversal filter characteristics prove out an operability of the technique.

1. Introduction

Microwave photonics (direct translation from Russian term – radio photonics) gives new possibility in microwave and millimeter wave signals processing. Many laboratories in many countries are involved in investigations in this field, and many microwave photonics applications were proposed for signal processing: photonic ultra wide bandwidth beamforming for phased array antennas (PAA), generation of microwave complicated signals, very high sampling photonic analog-to-digital converters, photonic filters for microwave signals, radar signal processing etc. [1-6]. Among these research works very interesting application is photonics beamforming for phased array antennas. Photonics usage strengths with respect to PAA (in comparing with conventional radio electronic beamformers mainly based on usage of really phase sifters) are: ultra wide instantaneous frequency bandwidth, and no beam squint effect in this ultra wide bandwidth (because of realisation true-time delay (TTD) approach in beamforming), low large distance signal transmitting losses in optical domain, small size and weight, immunity to electromagnetic interference and flexible designing [2, 3, 7, 8]. Our last 5 years interest was in photonics beamforming system (BFS) for linear PAA in receiver mode research and development some working BFS model also.

To provide a linear phased array antenna operation in several octave instantaneous frequency band, we have developed two models of photonic BFS [9-12], implementing the TTD principle for the control of the PAA beam after transferring the received microwave signals on the optical carriers. Our BFS models use dense wave division multiplexing (DWDM) technology with 100 GHz optical carrier frequency spacing in the wavelength range of 1.5 microns, so step in lasers’ wavelengths used as optical carriers for adjacent elements of PAA was $\Delta \lambda = 0.8$ nm.
An interchannel time delay compositions necessary for BFS beams formation were made on the base of chromatic dispersion usage in standard single-mode optical fiber SMF-28 segments of different lengths [9-11] and on the base of chirped fiber Bragg gratings [12]. These BFS models had an instantaneous operating frequency band 1..18 GHz. Figure 1 shows an architecture of our photonic beamformer models based on DWDM and wavelength depending interchannel delays $\Delta t_{IC}$. A detailed description of this scheme work can be found in [10, 12].

The PAA far-field pattern (FFP) width is estimated by equation $\theta \approx \lambda_r/d \cdot (N-1)$, where $\lambda_r$ is the wavelength of the microwave signal, $d$ is the PAA element spacing, $N$ is the number of elements in PAA. The FFP width (and angular resolution) varies when operating in such a wide (several octaves) frequency band, therefore the relative bearing of the sources may not be accurate enough. Figure 2 shows examples of the FFP direction control of one our photonic beamformer model [10]. The left graph is FFP for interchannel time delays $\Delta t_{IC} = 0$ ps, so the main lobe direction is 0°; the middle graph – for interchannel delays $\Delta t_{IC} = 21.6$ ps, the main lobe direction is 18.8°; the right graph – for interchannel delays $\Delta t_{IC} = 43.1$ ps, the main lobe direction is 36.8°. The interchannel delay value $\Delta t_{IC}$ depends on length $L$ of SMF-28 fiber segments used in TTD unit: $\Delta t_{IC} = D \cdot \Delta \lambda \cdot L$, where $D$ – SMF-28 fiber chromatic dispersion, approx. 17 ps/(nm·km) for C-band.

![Figure 1. The scheme of photonic beamformer based on DWDM and wavelength depending interchannel delays.](image1)

![Figure 2. Control of beam position of the 5-element PAA with photonic beamformer. FFP at 6, 9, and 12 GHz.](image2)

2. Microwave photonic transversal filter. Principle of operation
In photonic BFS it is possible to implement, by a small modification, an additional function of the broadband signal sources direction of arrival finding simultaneously with the PAA beamforming. This problem can be solved by development a microwave photonic transversal filter taking signals from
two PAA elements being delayed relative to each other on an optical carrier in the optical path [13, 14]. A transversal filter approves itself as a microwave notch filter, it has a periodic frequency response with a period \( f_0 = 1/t_F \). \( t_F \) is a mutual time delay introduced into the filter channels. When controlling the delay value \( t_F \) the filter notch frequency \( f_0 \) varies: \( f_0 = (0.5+k)/t_F \), where \( k = 0, 1, 2, \ldots \) [15]. The filter notch frequency can be adjusted to be in frequency band of the broadband microwave signal of interest coming to the PAA.

Figure 3 shows block-diagram of microwave photonic filter. We constructed this filter laboratory model with analog fiber-optic link’ components used in the BFS model before [10, 12], namely: two transmitters OTS-2T and one receiver OTS-2R (Emcore), a fiber-optic delay line VDL-001 (General Photonics) inserted in one arm of the filter, and a fiber-optic 2x1 coupler as summer before optical receiver. Transmitters OTS-2T have DFB laser optical carriers’ accordingly 100 GHz ITU grid with external optical Mach-Zehnder modulator (MZM) in it, its frequency bandwidth (for input microwave signal) – 0.1..18 GHz, transmitter power in fiber – very close to 10 mW. By line VDL-001 control one can change its time delay in band up to 330 ps.

Figure 3. Photonic microwave filter as part of photonic beamformer. ODL – optical delay line.

Figure 4 shows the filter main characteristic – its \(|S21(f)|\) measured by vector network analyzer (VNA) S5085 (Planar, Russia). One can see 3 notch frequencies \( f_0 \): 1.562 GHz (for \( k = 0 \)), 4.775 GHz (\( k = 1 \)), and 7.941 GHz (\( k = 2 \)). These frequencies correspond to the filter interchannel time delay \( t_F \) approx 318 ps.

Figure 4. The transversal filter frequency response as S21(f) measurement.
3. Wideband signal source direction estimation with microwave photonic filter - principle of its usage

We consider a situation that PAA with BFS main lobe is steered just to desired direction \( \theta \), \( \theta \) – angle from the normal to PPA “base line”. For this steering the BFS has to introduce mutual time delay \( \Delta t_{ic}(\theta) = d \cdot \sin(\theta)/c \) in microwave signals paths from antenna elements to these signals common summing node (after microwave signals transformation to optical domain there common summing node is photodetector), where \( c \) – the electromagnetic wave propagation speed. Because of BFS working in TTD mode all microwave signals at all PAA working frequencies at all antenna elements are in phase for this direction \( \theta \): received microwave signals mutual time delays are zeros when they are arrived for summing to photodetector.

If the signal source (which “occupies” wide frequency bandwidth) changes its direction by \( \Delta \theta \) within PAA main lobe, than the mutual delay \( \Delta t_{0} \) of the signals coming to the pair of selected elements of the PAA correspondingly changes: \( \Delta t_{0} = [L \cdot \cos(\theta) \cdot \Delta \theta]/c \), \( L \) – the distance between two PAA elements selected for microwave filter forming. The resulted mutual delay of the signals in the filter channels will be \( t_{f} = \Delta t_{0} \), which leads to shift \( \Delta f_{0} \) of the filter notch frequency \( f_{0} \). The notch frequency shift \( \Delta f_{0} \) is unambiguously related to the change \( \Delta \theta \) in source direction. It is nonlinear dependence, but for small changes we can use:

\[
\Delta f_{0} = (0.5+k) \cdot \Delta t_{0} \cdot (t_{f})^{2}, \tag{1}
\]

or \( \Delta f_{0} = (0.5+k) \cdot [L \cdot \cos(\theta) \cdot \Delta \theta]/c] \cdot (t_{f})^{2}. \tag{2} \)

The change in the signal spectrum is registered by spectrum analyzer at the filter output. When the filter notch frequency shifts it still remains within the signal spectrum (for case of broadband signal source). If some broadband signal sources simultaneously working in different frequency bands, say in S-, C- X- or Ku- band, are in PAA main lobe, we can look after them selectively by introducing the corresponding initial filter time delay \( t_{0} = 1/f_{50} \), where \( f_{50} \) – central frequency of broadband signal of interest, and examining the changes in spectrum around \( f_{50} \) frequency.

**Figure 5.** The microwave filter discriminate characteristic for 3 frequency regions (calculation).

**Figure 6.** The microwave filter discriminate characteristic for 2 frequency regions (experiments).

Figure 5 shows the filter calculated discriminate characteristic – \( \Delta t_{0} \) and \( \Delta f_{0} \) coupling as \( \Delta t_{0}(\Delta f_{0}) \) dependences for 3 central frequencies \( f_{50} \) (for case \( k = 0 \)): \( f_{50} = 1.5 \text{ GHz} \) when \( t_{0} = 333 \text{ ps} \);
$f_{S0} = 2.5 \text{ GHz}$ when $t_{F0} = 200 \text{ ps}$; $f_{S0} = 3.5 \text{ GHz}$ when $t_{F0} = 143 \text{ ps}$. From these dependences one can estimate, for example: for $f_{S0} = 3.5 \text{ GHz}$ notch frequency shift $\Delta f_0 = 200 \text{ MHz}$ corresponds to time delay change $\Delta t_S = 8 \text{ ps}$, and this time change corresponds to electromagnetic wave path change 2.4 mm. If the distance $L = 100 \text{ mm}$ and main lobe is normal to PAA base line ($\theta = 0$), than the source changes its angle within main lobe by $\Delta \theta = 1.37 \degree$. This is much less than this PAA main lobe half width (half width is a measure of PAA angular resolution) at $f_{S0} = 3.5 \text{ GHz}$.

4. Experimental results

Figure 6 shows results of experiments with the microwave filter laboratory model: the filter $\Delta t_S(\Delta f_0)$ dependences for 2 central frequencies $f_{S0}$ (case $k = 0$): $f_{S0} = 2.5 \text{ GHz}$ and $f_{S0} = 7.5 \text{ GHz}$. Our filter model components were named in part 2 of the article. In experiments we change time delay $t_F$ by VDL-001 and measure by VNA notch frequency shift $\Delta f_0$, see marks as ‘dots’ in figure 6. Figure 6 also shows theoretical dependences, see solid lines. RMS deviation of experimental points from theoretical dependences is 1.1 ps for $f_{S0} = 2.5 \text{ GHz}$, and 0.5 ps for $f_{S0} = 7.5 \text{ GHz}$. These values can be used in filter error calculations.

Figure 7 shows result of another experiment with the microwave filter model. In this experiment we examine microwave filter notch frequency shifts in real wide band microwave signal spectrum with changes (by the VOL) in time delay in one of the arms of microwave filter. The wide band spectrum signal from microwave generator MXG N5182B (Keysight) is splitted (50%-50%) and applied to the two photonics filter inputs. The photonics filter output is registered by spectrum analyser MXA N5182B (Keysight). The microwave signal is QPSK signal with central frequency $f_{S0} = 2.6 \text{ GHz}$ and sample rate 100 MSpS, so we have signal with 160 MHz width spectrum only. In figure 7 one can see overlay of three spectra registered at the photonic filter output for three values of mutual delay $t_{F0}$ in the filter channels. Each spectrum clearly shows notch frequency $f_0$ position and its value change $\Delta f_0$ from spectrum to spectrum also. These measurements confirm the possibility of wideband sources direction measurement with the discussed photonic two-tap microwave filter, showing that the time delay, and from it the source direction, can be measured.

![Figure 7](image_url)

Figure 7. The wideband spectra registered at the photonic filter output: shift of there notch frequencies.

5. Conclusion

This paper presents both the results of controlled far-field pattern measurements for PAA with model of ultra-wideband microwave photonic beamformer realized true-time-delay approach, so the characteristics of microwave photonic 2-channel transversal filter. The filter is simple subsystem of the developed photonic beamformer. The filter can processes some simultaneous wideband sources
within the PAA beam if there spectrum not overlapped. The technique has been experimentally demonstrated, and the experimental results are in a good agreement with the calculated results.

References
[1] Capmany J, Li G, Lim C and Yao J 2013 Optics Express 21 22862–67
[2] Urick V J, McKinney J D and Williams K J 2015 Fundamentals of microwave photonics (Hoboken, NJ: Wiley)
[3] Iezekiel S 2009 Microwave Photonics: Devices And Applications (Chippenham: Wiley-IEEE Press)
[4] Starikov R S 2016 Proc. SPIE 10176 1017618
[5] Davydov V V, Ermak S V and Karseev A U, Nepomnyashchaya E K, Petrov A A and Velichko E N 2014 Lecture Notes in Computer Science 8638 694-702
[6] Davydov V V, Dudkin V I, Velichko E N and Karseev A Yu J. Opt. Technol. 82(3) 132-135
[7] Tur M, Yaron L, Rotman R and Raz O 2011 Proc. OSA/OF/C/NFOEC 2011 (Los Angeles) OThA6
[8] Blanc S, Alouini M, Garenaux R, Queguiner M and Merlet T 2006 IEEE MTT Trans. 54 402-11
[9] Ivanov S I, Lavrov A P and Saenko I I 2015 J. Opt. Technol. 82(3) 139-46
[10] Ivanov S I, Lavrov A P and Saenko I I 2015 Lecture Notes in Computer Science 9870 670-79
[11] Ivanov S I, Lavrov A P and Saenko I I 2018 Proc. SPIE 10774 107740W
[12] Volkov V A, Gordeev D A, Ivanov S I, Lavrov A P and Saenko I I 2016 J. Phys.: Conf. Ser 737 012002 (6)
[13] Vidal B, Piqueras M A and Marti J 2006 J. of Lightwave Technology 24(7) 2741-45
[14] Pappert S A, Chang C-T and McLandrich M N 1987 Fiber and Integrated Optics 6(1) 63-77
[15] Zhang W, Williams J A R, Everall L A and Bennion I 1988 Electron. Lett. 34(18) 1770–72