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ORIGINAL PAPER

Performance analysis and comparison of optical signal processing beamforming networks: a survey

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Abstract
Forthcoming wireless systems are developed to support greater data rate and extra coverage area. This can be achieved with the help of multiple input multiple output and smart antenna techniques. One of the major rapidly emerging areas of communication is the smart antenna system which aids in attaining better coverage by increasing the signal strength only in the chosen direction. With effective optical beamforming techniques, the smart antenna systems demonstrate to be more competent in terms of excellence of signals in wireless communication. In this paper, a succinct outline of the smart antenna, an analysis and the comparison of different architectures of optical signal processing beamforming network (OSPBFN) is presented. The performance of OSPBFN is analyzed and the comparison is done for different architectures with the antenna radiation parameters. This paper can enhance the understanding of the ongoing research work in the area of OSPBFN.

Keywords Optical signal processing · Beamforming network · Smart antenna · True time delay · Optical ring resonator · Fiber Bragg grating

1 Introduction

Future mobile communication systems will have to support a growing demand for assorted broadband services and applications. With the restricted band existing, it has to provide high data rate communication for increasing cellular subscribers. The exploitation of smart antennas is expected to increase in general the system capability and concert [1–10]. A smart antenna combines a number of antenna elements with a signal processing unit [11–15] to improve the beam pattern for transmission and reception automatically. Smart antenna technology [16–20] offers a considerably enhanced solution to decrease interference levels and increase the link range and enable frequency reuse of the channels. By means of this technology, the base station (BS) [21–25] transmits and receives the signals only in the direction of the intended user. This significantly condenses the link power budget as well as the overall interference in the system.

Beamforming is a technique where the intricate weights corresponding to the phase and amplitude of the signals to be transmitted from the antenna are multiplied with the signal of each user. So that the transmit/receive beam is formed from the output array of antennas in the preferential direction and is diminished in the unwanted directions. Smart antennas are classified into two groups. One process is called as switched beamforming [26–33], if the beams are formed in the explicit, prearranged directions from the intricate weights which are chosen from a library of weights. In this process, the BS mostly toggles between dissimilar beams based on the strength of the acknowledged signal. The other process is called as adaptive beamforming [34–42] where the adaptive algorithm calculates and updates the weights adaptively in real time. In this process, the BS forms narrower beams in the track of the most wanted client and nullifies the interfering client. This significantly improves the signal-to-interference-plus-noise ratio.

Beamforming network (BFN) is a circuit which performs beam direction finding in addition to beam shaping.

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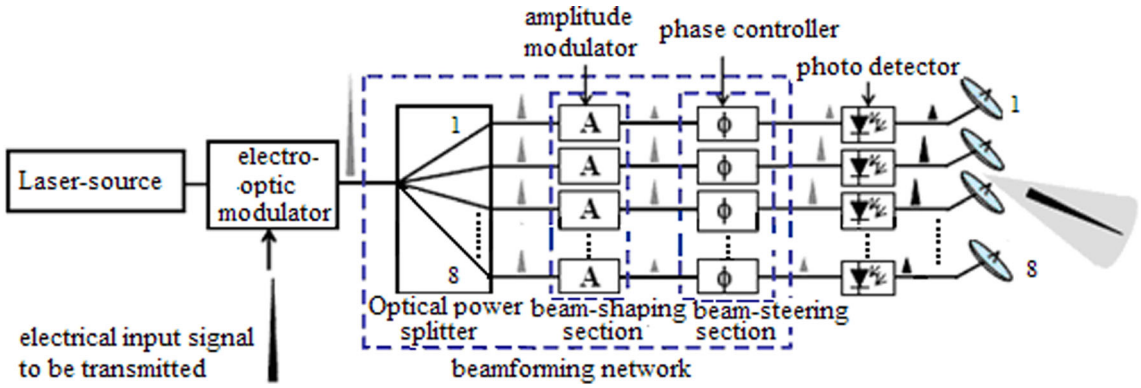


Fig. 1 Simplified schematic diagram of an OSPBFN

BFN combines the antenna arrays with signal processing to steer themselves automatically to receive the signal in response to the direction of the incoming signal and separate the signal from the direction of interference. A diversity of tasks such as beam steering, beam shaping, beam scraping and multi-beam transmission can be done by BFN. Electrical beamforming technique RF beamforming technique, digital beamforming technique and optical signal processing beamforming technique are the classification of beamforming techniques for antenna arrays.

Electrical BFN has severe disadvantages when high-bit rate signals are to be transmitted. Electrical circuits operating at these higher frequencies have a tendency to be huge, lossy, heavier and more vulnerable to electromagnetic interference. RF beamforming is the most universal technique which is broadly used in small-scale integration [43]. However, it has the problem that as increasing the antenna size, circuitry arrangement is difficult, bulky and hence high-priced hardware is required for large-scale integration. If signal processing is done in the digital domain for digital beamforming technique [44–60], highly flexible algorithms are utilized to modify the received signal. The rate of the digital signal processor is limited within 100 MHz. The optical signal processing techniques with adaptive algorithms will increase the speed, channel capacity and data rate for mobile communication. Signal allotment and processing task in the optical field together is provided by the OSPBFN. Optical signal processing (OSP) method reduces the complexity of the traditional system to a great extent and raises the speed.

This paper is prearranged as follows. Section II portrays the overview of OSPBFN and gives a literature review of existing OSPBFN developed by various researchers. In Section III, the performance comparison between the different existing OSPBFN methods is also explained. Chapter IV concludes the paper by summarizing the major contributions of the survey and its applications.

2 OSPBFN technique

The OSPBFN itself is free from RF frequency since the optical frequency is comparatively several folds higher than the RF frequency. Owing to the optical components, the renowned advantages of OSPBFN are broad bandwidth, low throng, small size and protection from electromagnetic interferences. Furthermore, the signal processing is done in parallel; the optical components required are reduced to $M + N$ from $M \times N$ in the case of RF BFN.

The simplified schematic of OSPBFN for eight antenna elements is presented in Fig. 1. The electrical signal is given as input to the electro-optic modulator, and the modulated optical signal is split by 1×8 optical power splitter. The output of the power splitter is coupled to the amplitude controllers. It controls the amplitude of the signal and ultimately finds out the width of the main lobe and the sidelobes levels, and this process is called as beam shaping. Beam shaping is performed by optical attenuators. Subsequently, the optical phase shifter adjusts the phase of the signal which comes out of the amplitude controller. Therefore, the phase delay difference establishes the track of the transmitted signal. This method is called beam steering. Before each amplitude and phase controlled signals are sent to the particular antenna element, the photodetector converts the RF signal to an electrical signal and transmitted out toward the end user.

3 Review of existing OSPBFN

An active OSPBFN is expected to be efficient for the applications such as mobile radio communication, wireless LAN and satellite communication. Monolithic microwave integrated chip for a large number of users involves very convoluted, serious and expensive BFNs. Though enormous researches are going on in digital-based BFNs, bandwidth is the limitation. The research on photonics technology in microwave array antennas is enduring over the past decades. For the

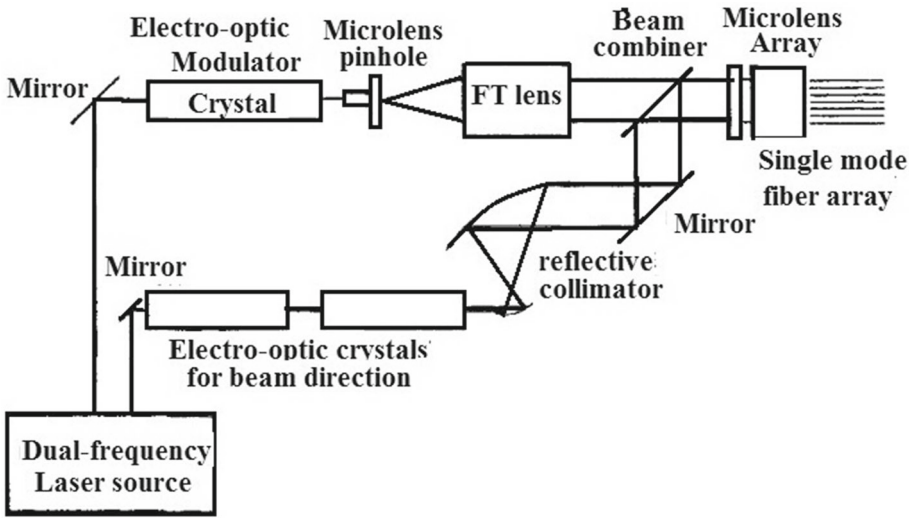


Fig. 2 Schematic of FT lens OSPBFN [51]

specific frequency range, a key obligation in the OSPBFN is to reduce the amplitude and phase tracking errors of all the sub-systems. This requirement directly impacts the radiated beam pattern which gives reduced beam squint, satisfactory sidelobe levels and increases the beam pointing precision.

3.1 Fourier optics-based OSPBFN

The Fourier transform (FT) optics is used for optical signal processing which provides high speed of signal processing operation. By means of a FT lens, beam scanning and beamforming are carried out by merely keeping the laser source in the central plane of the FT lens. Initially, in the year 1980, Koepf [61] investigated a very well-designed beamforming technique based on Fourier optics. The schematic of FT lens method OSPBFN is shown in Fig. 2. One of the two laser beams was intended for an electro-optic modulator and focused on the pinhole, which symbolizes a circular antenna beam signal. The beam combiner combines the first beam and the second beam which was passed two electro-optic crystals. The superposition of the fields was obtained by the group of single-mode fibers which were used to send the two signals to the phased array, where the photodetector was inbuilt. Afterward, a team led by Goldberg and Stilwell [62, 63] at the NRL laboratory had performed experiments on this approach.

Among few practical systems for multi-beam applications, the combination of spatial Fourier optical processing scheme and optical heterodyning method was used to feed optically the microwave array antennas and this work was done for multi-beams by Ji et al. Extra number of lasers and the fibers were required for this method, according to the antenna elements. They compared the theoretical and experimental antenna radiation pattern of the two-multi-beam antenna. The phase and amplitude disturbance noted were 3° and 0.4 dB.

Akiyama et al. [66] developed 2D FT OSPBFN which was the advanced version of the 1D FT OSPBFN. In this method, the far-field radiation pattern of an antenna was the FT aperture distribution, and the amplitude and phase distribution on the aperture is excited by the RF beat signal of two laser beams on the optical fiber array input plane, which was the image focal planes of the FT lens; therefore, the most wanted antenna pattern was attained by the focal plane of the FT lens. The different master lasers were linked with the fiber and were kept in the vicinity of the FT lens. The optical beam sent out to the fibers was Gaussian beams. When the signal departed to the FT lens, the beams were pointed to the image plane with the same Gaussian amplitude values and different phase values. The authors used the multilayer polymeric optical waveguide arrays to generate and control a 2D-specific phase front and sample 2D distributed light beams. In this work, degradation in gain is discovered to be 3.8 dB.

To comprehend a good control over the antenna radiation pattern, the same group of authors [67] discussed with an amplitude spatial light modulator (A-SLM) to form images onto the FT optically. An antenna radiation pattern was experimentally measured in the C-band. Further, a miniature FT-OBF was realized by a combination of three different types of lenses. The length of the entire optical system was with a reduction of 1/5 length as compared to the length by means of a single lens. It was found that the main beam of the radiation pattern was focused at 13° and bandwidth was very wider. Further, the same group of authors developed the FT optical beamformer experimentally to steer the RF beam in the C-band [68]. After this publication, none of the research work was published for FT lens-based beamformer to the best of the knowledge of the authors.

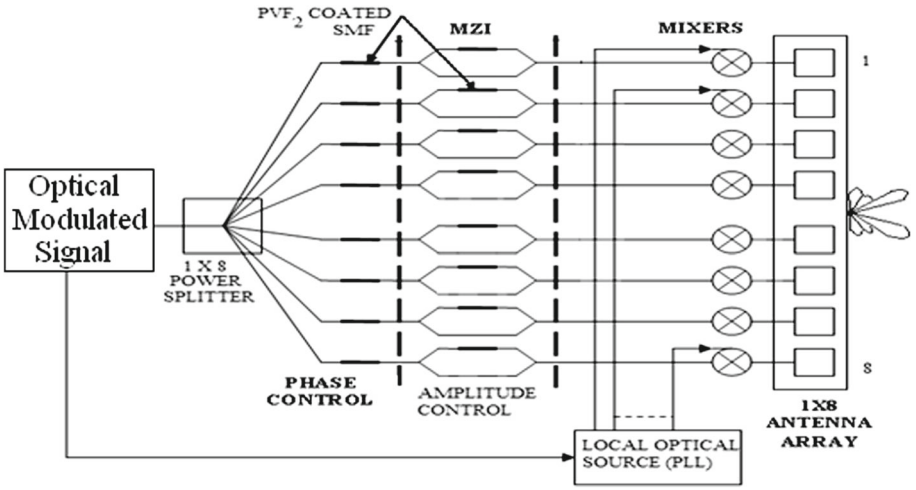


Fig. 3 OSPBFN using coated SMF arrays [72]

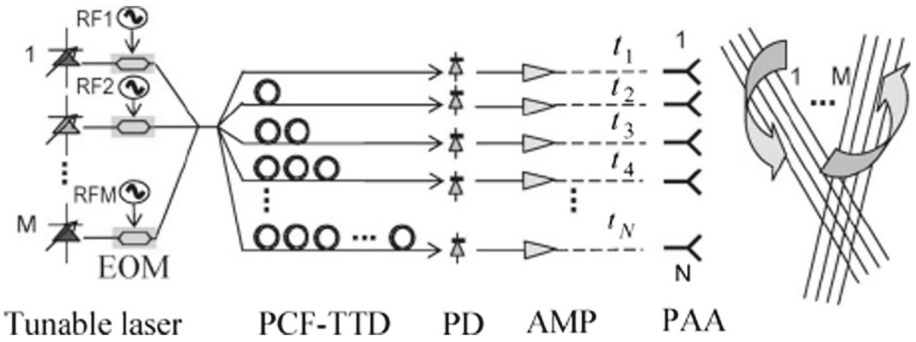


Fig. 4 Block diagram of PCF beamformer [74]

3.2 Fiber based OSPBFN

The OSPBFN [69] was experimentally implemented using two optical fiber networks to yield a beam having individually identified frequency and aperture phase slope. In this work, **f**or achieving phase and amplitude shifting, 150 meters of fiber were required. They found that many of the problems were associated with lengthy optical fiber and poor radiation patterns.

An experimental setup using fiber for a beamforming network of 60 GHz mobile communication systems was reported by [70, 71]. Silica-based beamforming network was integrated as IC which had both phase distribution and amplitude distribution sections. The BFN operated independently of the millimeter wave frequency because the phases and amplitudes were controlled using the thermo-optic effect in the optical realm before getting of the microwave by the support of a photodetector. This OSPBFN had also been implemented with the drawback of slow millisecond type response, more no of heaters and limited isolation performances.

A single-mode fiber encrusted with polyvinylidene fluoride (PVF_2) demonstrated the inverse piezoelectric effect [72]. The uniform strains were passed into the piezoelectric fiber by applying a voltage to the coated fiber. The length was changed due to the applied voltage, and in turn, the refractive index of the fiber was modified because of strain along the fiber axis. Successively, an optical phase shift $\Delta\phi$ was produced. The output of the 1×8 power splitter was provided for the PVF_2 coated optical fibers to generate phase control. Mach–Zehnder interferometer controlled the amplitude of the signal. The optically processed signals were heterodyned with the optical signal from a local optical phase-locked loop (PLL). In heterodyning, the local optical PLL frequency ω_{LO} and the signal carrier frequency ω_0 were properly selected to produce 2 GHz microwave signal as the intermediate frequency ω_{IF}. The microwave signals were given to a 1×8 array antenna elements, and the antenna spacing was $d = \lambda/2$ as shown in Fig. 3.

A group of authors Chen et al. [73, 74] and Subbaraman et al. [75] introduced first time the high dispersive photonic crystal fibers (PCFs) as true-time-delay (TTD) element as shown in Fig. 4. The RF signal is modulated by an electro-optic modulator and was fed to the PCF-based TTD module. Each TTD line had different spans of PCF segments. The wavelength of the laser is tuned to provide a time delay for N-element OSPBFN to steer the beam continuously. The optical signal was converted into the corresponding electrical signals by the N photodetectors. The electrical signals were amplified by amplifiers and then fed to the OSPBFN. The negative

aspects of these methods were listed as: look directions (LD) error was small (Not specified). The scanning sector was +45° to −45°; this method required PCF of length 10.5 m; null directions (NDs) were neglected; half power beam width (HPBW) was 55°; and the main lobe was very broad.

The model of photonic beamformer presented by Volkov et al. [76] for wideband microwave OSPBFN was investigated for the receive mode only. The approaches applied for the photonic beamformer were dense wavelength division multiplexing (DWDM) technology and optical fiber chromatic dispersion. Microwave linear array antenna of 5-elements was experimentally analyzed, and the far-field patterns were measured in 6–16 GHz frequency range. The antenna was steering up to 40°. The LD and NDs, HPBW were not mentioned.

In recent years, multi-core fiber (MCF) has been developed for the application of fiber optics beamformer. Airat Zainullin et al. [77] proposed a MCF-BFN for broadband satellite communications. The reduced size and weight of the MCF were the advantages of this beamformer. Compact optical BFN was implemented by exploiting the space division capacity of MCF for four-element antenna array. The main drawback of this architecture was a relatively high insertion loss which can be reduced by using fixed attenuators. The analytical evaluation of the MCF beamformer such as cross talk, scalability was also done.

3.3 TTD method OSPBFN

An optical TTD line can be used for multi-beamforming equally in transceiver modes. TTD beamforming for OSPBFN was studied widely for the past two decades. Due to the capability of integration of the TTD, this method offered several benefits such as firmness, less weight, low propagation loss, high instant bandwidth, simplified transmitting/receiving architecture, squint-free beam scanning frequency independence and inherent immunity to electromagnetic interference. Different versatile methods for TTD beamforming system were recommended and demonstrated such as fixed-length optical fiber delay lines, fiber-optic dispersive prism TTD, discrete fiber Bragg gratings (FBG), chirped fiber gratings [78–81], discrete-chirped fiber grating [82, 83] and piezoelectric fiber stretchers.

The earliest microwave phased array antenna (PAA) was designed using an optical delay line (ODL) and was demonstrated by Ng et al. [83]. Semiconductor laser switching was implemented for providing the delay. It was observed that the scanning sector was − 28° to + 28°. Shibata et al. [84–86] and Inakagi and Karasawa [87] demonstrated spatial optical signal processing array antenna using optical TTD units to scan over 0°,90°,180°,270°. The advantages of this method were reduced circuit complexity, size and weight.

The realization of tunable TTD based on a fiber-optic prism was demonstrated by Esman et al. [62, 63]. In this system, TTD feed was formed by splitting and sending the optical signal into a fiber-optic prism which consisted of high-dispersion and non-dispersive fiber. Hence, the optical wavelength was adjusted and the different delay was produced in each fiber link. Figure 5 illustrates the beamforming system based on fiber-optic prism TTD. Antenna radiation pattern was measured in the ranges of 2–8 GHz. The main lobe steered to − 9.4° and + 3.4° for the wavelength of $\lambda =$ 1535 nm and $\lambda = 1580$ nm, respectively.

Tulchinsky and Matthews [88] proposed the fiber-optic dispersive prism approach TTD in the main beamformer. This fiber dispersive prism was capable of producing a time delay based on wavelength to the point of the consequent element in the array. An optical-dispersion gradient accomplished this delay. The system exhibited no beam squint across a ± 60 azimuthal span. Arrayed waveguide grating can be used as ODL in optical BFN [89]. The ODL presented multiple simultaneous TTDs to achieve the multi-beam capability. Though these approaches were promising approaches, the major limitation was the requirement of long fibers (in terms of m & km) and narrow scanning sector (+ 22° to − 20°).

The combination of a multi-wavelength laser and a digital delay line consisted of a fast switch matrix and dispersive fibers used as beamformer [90]. The variation in optical path length introduced relative delays for different wavelengths. The similar beamformer was used by the transmitter and the receiver.

The beamformer architecture reported by Lavrov et al. [91] was based on TTD and chromatic dispersion in fiber and implemented using DWDM and fast fiber-optic switching. This architecture was designed for total wavelength band $(N - 1)\ \Delta\lambda$, having N number of lasers with equidistant wavelengths and N number of linear phased antenna arrays. The intensity modulated optical carriers were multiplexed by $N \times 1$ multiplexer and applied into a time-delay unit. The high-speed photodetector was used to detect the aggregate radiation of all wavelengths. The beamforming system transfer gain was − 29 dB for $N = 32$ and rises to 0 dB when $N = 1024$.

Jiejun Zhang and Jianping Ya [92] experimentally demonstrated a wavelength-dependent TTD BFN based on a switch-controlled recirculating dispersive loop. The input microwave signal was modulated on multi-wavelength optical carrier signals of a laser array. The modulated signals were applied to the recirculating dispersive loop which depends on the wavelength. The optical signal recirculated in the loop for multiple round trips and provided a wavelength-dependent time delay. The delayed microwave signals were fed to a PAA. It was found that multiple round trips of the optical signals in the dispersive loop produced a different beam pointing direction. Zero, one, two and four round trips

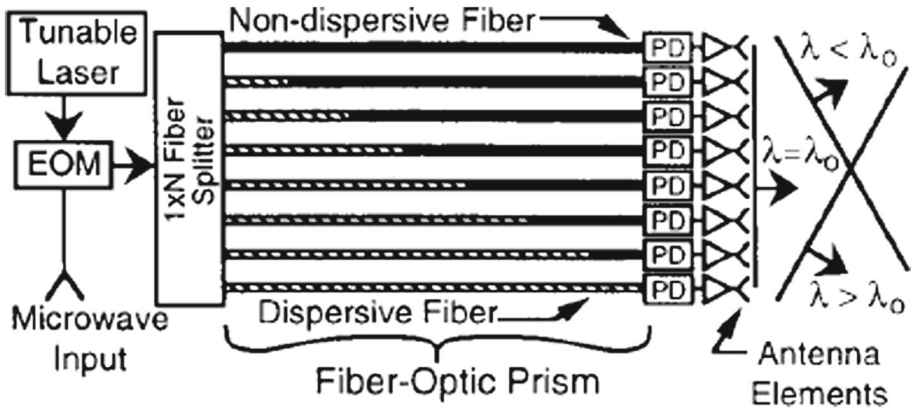


Fig. 5 Beamforming system based on fiber- optic prism TTD [62]

produced a beam pointing the direction of 0°, 8.6°, 17.5° and 36.9°, respectively. The antenna is steered from −60° to 60°.

The TTD element based on discrete FBG for beamforming system has numerous advantages, including less jitter, wide bandwidth, low cost and less complex in production. Various researchers [78–80] had validated an optical fiber grating-based true delay line for a beamforming network. An equally spaced, single fiber with high reflectivity was considered. The grating had diverse central wavelengths disseminated along its length. The system operated at frequencies in the range 500–900 MHz with a minimum time delay of 31 ps. A PAA beamforming system using the discrete FBG-TTD unit based on discrete FBGs was designed to work at high frequency [79, 93]. The critical parameters of TTD unit were the spacing between adjacent gratings which determined the time delay in the beam pointing direction and also the position of the gratings equivalent to the same wavelength in end-to-end fibers. In most of the investigation, these parameters were assumed to be equal. If these values were not equal, the TTD unit can provide high-resolution time delay and precise direction of steering for high-frequency signals. The scan range of ±60° for frequency 40 GHz was achieved from this system.

Two-dimensional planar PAA is having a good attraction for many practical applications. The combination of wavelength-dependent and -independent time-delay units was used for achieving 2D beamforming system [94, 96]. The optical beamforming system consisted of wavelength-dependent TTD unit based on FBG and wavelength-independent TTD unit based on microelecromechanical system (MEMS) switch. This was used to control the azimuth beam steering and elevation beam steering correspondingly. The time-delay errors and its corresponding radiation direction error were less than 11.8 ps, 3.6 ps and 1.5°, 0.4°, respectively, for a planar PAA with λ/2 spacing between the adjacent array elements. The hitch of this method was a high LD error (6.3%), narrow scanning sector (−24° to +24° in azimuth and 0 to 40° in elevation) and negligence of NDS. These architectures required a large number of optical switches and resulting non-uniform and higher insertion losses in the delay line.

Howard et al. [96] proposed FBG prism-based TTD beamformer incorporating a wavelength-dependent optical PLL. In this system, four discrete FBG delay lines were used and its spectral width was of about 0.1 nm near 1549 nm. The angle of the steering was around ±28° from broadside. In an approach [97], a series of similar compact fiber grating prisms produced TTD by the reflected signal from the two reverse directions of the FBGs. Therefore, the system was more compact and required the minimum number of optical switches. The antenna steered in azimuth directions was 2.22°, 11.4°, 32.6°, 37.2° and 66.8° for the RF frequency 5 GHz.

Anliang et al. [98] demonstrated a programmable optical beamformer for multi-channel and multi-bit. This beamformer structure consists of N number optical TTD sub-networks, connected parallelly by an optical splitter. Each PTTD sub-network has cascaded connection of DWDM, was realized by wavelength controlled multi-channel TTD and provided multi-bit TTD for a multi-channel modulated RF signal of a PAA and operated over a wide spectrum from 10 MHz to 12 GHz. Though the structure was bulky with large size, it was a favorable candidate for wideband radar and wireless communication applications. In this architecture, amplitude ripples of all channels for each TTD were less than 1 dB and LD error was 5%. Also average sidelobe level was −20 dB. Duarte et al. demonstrated a real-time photonic 4 × 1 TTD optical beamformer. The data rate of the Beamformer for 28 GHz—QPSK modulation was 1 Gb/s [99].

In an optically controlled radio beamformer [100], the optically controlled TTD lines were used for beam steering. The light signal from the tunable laser and the modulating signal from M array antenna elements were applied to the Mach–Zehnder modulator, and its output was passed to the photodetector through optical TTD lines. The recovered electrical signal from the photodiode was the delayed version of the RF input signal. Beam steering can be achieved by com-

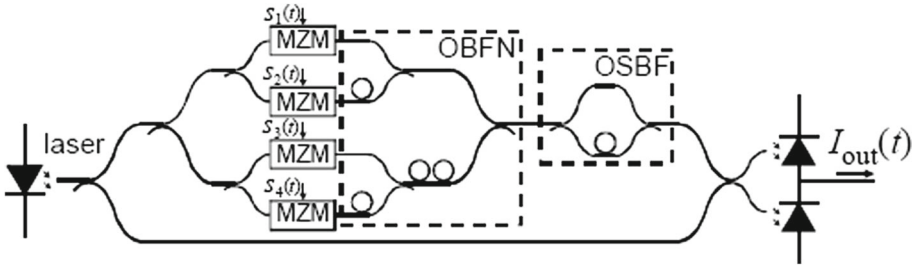


Fig. 6 Schematic of the ring resonator-based OSPBFN

bining the delayed signal with an undelayed input signal. The TTD beamformer designed for 19.5 GHz was able to steer the beam from – 28° to 34°. The same group of authors experimentally verified 4x1 phased array with an optical feed network for K-band smart antenna systems. Beam steering was obtained up to 45°. A wireless transmission data rate was achieved up to 3 Gbit/s using 32-OFDM subcarriers [101].

Optical frequency combs comprised of chains of equally spread out frequency lines. Different comb lines were selected and used as tunable TTD elements. Photonic TTD beamforming network with 21 elements using miniature optical frequency comb source and dispersive time delay was experimentally done by Xiaoxiao Xue et al. [102]. The beam pattern was controlled by weighting the signal in the optical domain by combining optical phase modulation and programmable spectral shaping. The optical beamformer was analyzed for the frequency of 8–20 GHz, and the beam scanning angle was $\pm 60.2°$. The improved version of the previous work TTD was based on a combined microring resonator (MRR), and the frequency used for Kerr optical comb was 49 GHz. A single channel of comb source corresponded to 81 channels over the C-band and was experimentally verified by Xiaoxiao Xue et al. [103].

3.4 Optical ring resonator-based OSPBFN

Optical ring resonators (ORRs) can be used to implement the tunable ODL which formed PAA. Single-chip realization of OSPBFN based on ORRs as tunable delay elements were fabricated by Zhuang et al. [104] and Liu et al. [105]. Further, 1×8 OBFN chip [106] had been fabricated in a CMOS-compatible waveguide technology. By simply adding more stages of ORRs, again the 1×8 ORR-based OSPBFN ([107–109] was demonstrated using single-sideband suppressed carrier modulation as shown in Fig. 6. However, the developed ORRs suffered from two major drawbacks: (1) The coupling factors were adjusted manually and (2) 31 heaters with a total power of 8 W were required for an 1X8 OSPBFN. Hence, if coupled ORRs were to be used in the PAA, an automatic fast method to adjust the coupling factors was necessary. Figure 6 depicts the architecture of OSPBFN based on ORR. In this figure, MZM represented Mach–Zehnder modulator, OBFN and OSBF denoted optical beamforming network and optical sideband filter, respectively. In this structure, the trade-off was between bandwidth and number of rings used. The essential number of rings was approximately proportionate to the product of required optical bandwidth and maximum delay.

The basic idea behind ORR-based OBFN using multiple wavelengths was to create multiple signal paths on the same beam former. The network complexity, the required number of rings and heaters were reduced by carrying the signals of different antenna elements by a single delay line. This idea was made possible by the use of the frequency periodic behavior of the ORRs [110].

A 1×4 integrated OBFN based on ORR was demonstrated by Liu et al. [111, 112]. The TTD response of a 3-ORR delay line with a bandwidth of 6.3 GHz and 8.7 GHz was realized over the fine-tuning range of 208.7 ps and 172.4 ps, which related to a phase shift of 31π of 17.1π and 14.1π phase shift for a 90 GHz signal. The beam steering angles 49° and 22° corresponding OBFN delay response were attained for a 90-GHz half-wavelength dipole antenna array.

3.5 SLM and MEMS-based OSPBFN

Spatial light modulator (SLM) is one of the key components of many OSP operations. It provides an optical time delay line and controls the phase of the signals feeding to the antenna [113, 114]. Etem and Lewis [115] demonstrated an optical beamformer incorporating a 360° phase SLM. Optical beamformer was connected to a nine-element antenna by 100-meter of ribbon fiber. This method had the disadvantages of higher power laser source, lengthy fiber and could not be utilized for higher BW.

First time Wilson et al. [116] investigated MEMS-SLM-based OSPBFN. The designed OSPBFN consisted of an array of microscale mirrors that were electrically controlled to move them vertically. Light reflected from a piece mirror underwent a phase shift depending on the distance the mirrors had moved. The main advantages of optical-MEMS-based optical beamformer were smaller and low complexity.

The OSPBFN architecture [117] was based on providing time delays introduced by fiber-ODL. Parallel-alignment SLM (PAL-SLM) produced adequate phase shifts to the signals which fed to the different subarrays. The specific input

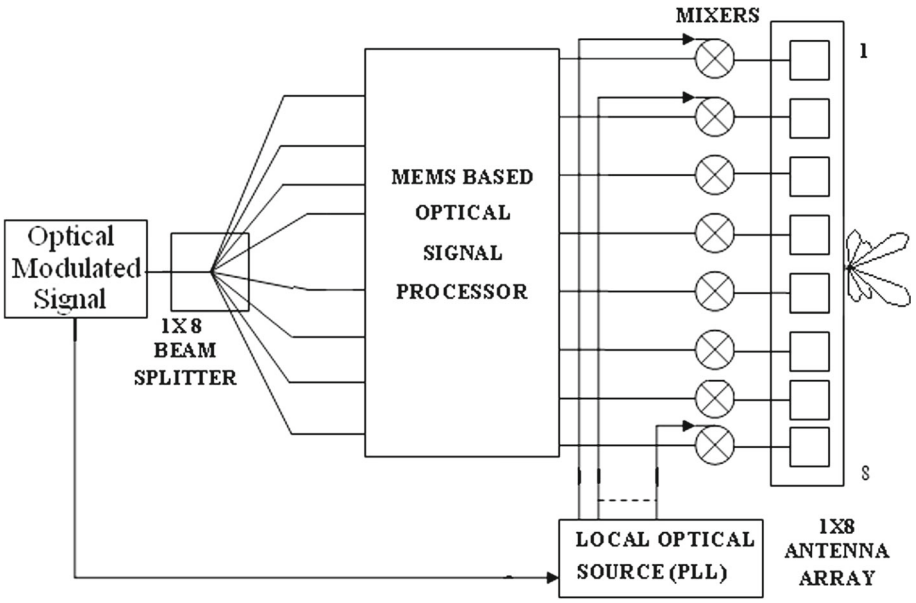


Fig. 7 Schematic diagram MEMS-based OSPBFN

driving voltage controlled the PAL-SLM. The modulated signal was amplified by the Erbium-doped fiber amplifier and time delayed in the different group ODL module. Then, the signals were launched to free space with the help of fiber collimators, where a PAL-SLM was used to control the phase shift of every pixel element. Finally, photodiode converted the output optical signals to RF and transmitted through the antenna. This architecture had the drawbacks of high LD error (6%), small scanning sector ($-20°$ to $+20°$) and unsatisfactory sidelobe suppression.

MEMS-based method for OSPBFN [118, 119] consisted of two micromirrors that were freely moving to control the phase and amplitude of the optical signal. The schematic diagram of MEMS-based OSPBFN is shown in Fig. 7. The micromirrors were driven by a comb-drive electrostatic actuator. The voltage applied to the electrostatic actuator was calculated from the weights of the maximum directivity algorithm. The path of the optical signal and the beam axis were changed in accordance with the phase shift and amplitude weights. Each signal is subjective by controlling the phase and amplitude using a couple of micromirrors driven by electrostatic comb-drive actuators. The processed optical signal was heterodyned with a local optical source signal which was phase-locked to the input signal. The resulting weighted RF signal was then fed to the equivalent element of the 1×8 antenna array $\lambda/2$. It was observed that HPBW of the main lobe was 15°. Average sidelobe level was -20.5 dB. An average null level was -42.4 dB.

3.6 Acousto-optic liquid crystal-based OSPBFN

Both the acoustic-optic effect and liquid crystal are either separately or combined used in the applications of the optical beamformer. In the early nineties, acousto-optic liquid crystal-based phase control was experimentally proved by Dolfi et al. [120] and Kobayashi and Ogawa [121, 122]. The problem associated with this antenna was the requirement of the bulky optical components.

Riza [124–126] had successively demonstrated a novel processing technique that allowed for independent phase and carrier control using single-sideband signals for the acousto-optic PAA beamformer. The author observed that single-point phase fluctuations of $\pm 4°$ in the initial experimental work. The phase fluctuation was improved too $\pm 2°$ of in his further work.

Acousto-optic beamformer was investigated and demonstrated by Antony et al. [127] theoretically and experimentally. In the acousto-optic beamformer, the spatial filter strengthened the audio signal that extended perpendicular to the beam of light and deteriorated otherwise. Beamforming patterns were measured with a collection of 19 microphones and a spacing of 3.75 cm and steered at 0°, 45° and 90°.

Lin et al. [128] proposed a beam steering control device based on liquid crystal spatial light modulator (LCSLM). The experiment setup was made as shown in Fig. 8. The phase of the incident light was altered by the optical path difference between the two lights as shown in the above figure. It contained 1920×1080 pixels with the extreme frame rate of 60 Hz. Therefore, the incident light was directed to the particular angle. The LCSLM was proficient at steering the shaft of light from -2.8947 to 2.8947° with a resolution of nearly 0.0226°. Tracking the performance was better than -17 dB.

Another phased array antenna [129] comprised of 1-by-4 dielectric resonator antenna (DRA) array, liquid crystal phase shifters, RF-feeding and biasing networks. The dielectric resonators were considered as waveguide radiating elements.

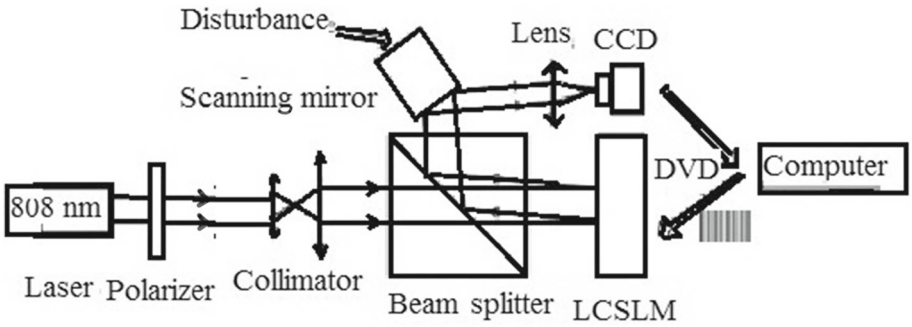


Fig. 8 The beam tracking experiment of LCSLM

The RF signal coupled between the phase shifters and DRAs was steered and then radiated from the top face of the DRAs. The surface waves were suppressed because of liquid crystal phase shifter, and hence, gain was also improved. The beam scanning range of ± 30° was obtained.

Xiangjie Zhao et al. [130] proposed a new setup to measure the real phase value in a liquid crystal optical phased array. The steering efficiency was enhanced from 80% to 90%, and the steering angle was 1° which was very poor.

Yi et al. [131] proposed optical beamformer consisted of microwave phase shifter based on liquid crystal on silicon (LCoS) pixels operated over 10–20 GHz. LCoS pixels were arranged with single input fiber and multiple output fibers. The LCoS pixels allowed active wavelength direction finding to the output ports, and the direct control of phase and amplitude was achieved in the optical domain and then converted to the RF domain. The beam steering angles of the optical beamformer were 20°, 40°, − 20°, − 40°. The resolution of amplitude control was 0.1 dB.

For different OSPBFN architectures, the beam steering error (in LD and NDs) or the beam squint was analyzed. It was found to be 9.3% (high) in [134], 6% [117], 6.3% [81], 6.6% [88]; LD error was high [64, 65, 123–125]. The LD error for the architectures proposed by Caroline et al. was 0.7–1.3% [118, 119] and 5% [98]. The average sidelobe level was summarized for different architectures. It was found to be − 17 dB [89, 90], and − 20 dB [118, 119]. Few OSPBFN architectures presented by Jofre et al. [117], Chujo and Tomiyama [133], Granieri et al. [134], Jiejun Zhang and Jianping Ya [92], the sidelobe suppression was unsatisfactory. The average null levels of different architecture were: − 30.4 dB [73, 74], − 42 dB very low level [118, 119], − 25 dB [98]. Most of the architectures ignored NDs. The performance of the optical beamformer was analyzed using the data rate of the wireless systems. The date rates for different modulation schemes were found to be 5.81Gbps for 8 QAM, 9.68 Gbps for 32 QAM [137], 1Gbps for QPSK [99] and 3GBps for OFDM 32 subcarrier [101].

4 Comparisons of OSPBFN architectures

All the above-mentioned different types of OSPBFN architectures are compared. In Table 1, overall comparisons of various parameters such as scanning angle, HPBW of the main lobe, average sidelobe level, beam steering error (in LD and NDs) and average null levels of the OSPBFN responses are being analyzed for all OSPBFN architectures and listed. It is clearly seen that the main lobe is narrow in few OSPBFN architectures and the sidelobe suppression is satisfactory. As far as the length of the fiber is concerned with [132, 115, 89, 90, 73, 74], the fibers are required in m, km. In contrast, the work reported by the authors [72], OSPBFN required 60 cm PVF_2 coated single-mode fiber. For this short length of the fiber, the signals are steered from − 60° to + 60°. The scanning sectors analyzed by Schippers et al. [108, 109] were 90° and 40° [117]. In Akiyama et al. [66] work, the scanning sector was moderate. Scanning sector was small (± 22°) for the architecture demonstrated in [89, 90] and 25° for the architecture proposed by Chujo and Tomiyama [133].

5 Conclusion

In this paper, a comprehensive survey has been done for recent research in OSPBFN antennas and also their advantages and disadvantages were discussed. Several methods have been analyzed for OSPBFN based on fiber optics as ODL, Fourier optics, acoustic-optics, integrated optics and WDM. Examples of the few recent concepts are dispersive PCF, FBG prism, inverse piezoelectric effect on SMF, ORR and MEMS-based micromirrors. These techniques were described in various sections, and relevant papers were introduced and studied in each section. Finally, an extensive comparison has been done for various key parameters such as scanning sector, HPBW of the main lobe, average sidelobe level and average null levels. In short, the surveyed papers are intended to enable ultra-fast multi-beam steering for smart antennas with an optimized radio link between the BS and the mobile station. These beamformers are applicable for mobile communication, satellite communication and radar with the high data rate of Gbps.

Table 1 Comparisons of Different OSPBFN Architectures

Sl. no.	Antenna parameters from radiation pattern	Comparisons of OSPBFN architectures
1	Scanning sector (°)	i. Maximum 90° [108, 109]
		ii. Minimum 40° [117]
		iii. The scanning sector is moderate [66]
		iv. The scanning sector is small (±22°). [89, 90]
		v. 25° [133]
		vi. −28° to +28° [83]
		vii. +60° [84, 85]
		viii. ±45° [73, 74]
		ix. −24° to +24° in azimuth and 0 to 40° in elevation [95]
		x. ±60° [118, 119]
		xi. 20° [135]
		xii. 45° [100]
		xiii. 0° and 13° [67]
		xiv. 0°, −14° and −28.5° [92]
		xv. The antenna is steering up to 40°. [76]
2	HPBW of main lobe	i. 17° [117]
		ii. 35° [89, 90]
		iii. 55°; the main lobe is very wider, and power is wasted [73, 74].
		iv. 31° [134]
		v. 15° Satisfactory. [118, 119]
		vi. 20° Satisfactory [136]
		vii. 40°; the power is wasted in the main lobe [67]
		viii. 10° [92]
3	Average sidelobe level	i. −17 dB [89, 90]
		ii. −11 dB [117]; the sidelobe suppression is unsatisfactory.
		iii. The sidelobe suppression is unsatisfactory. [133]
		iv. High sidelobe level [134]
		v. −20 dB; satisfactory sidelobe suppression. [118, 119]
4	Beam steering error (in LD and NDs)	i. 9.3% The beam squint is high. [134]
		ii. 6% [117], 6.3% [95], 6.6% [88]; the beam steering error is slightly high.
		iii. LD error is high. [64, 65] [123–126],
		iv. LD error is low value, but not specified [73, 74]
		v. 0.7% to 1.3% [118, 119]; the beam steering error is very low.
		vi. 5% [98]
		vii. The error was not specified in other architectures.
5	Average null levels	i. −30.4 dB [73, 74]
		ii. −42 dB very low level [118, 119].
		iii. −25 dB [98]
		iv. −30 dB [92]
		v. The null directions are ignored in all the architectures.

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