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# Optical signal processing beamforming network-a survey paper

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**ABSTRACT**

Mobile communication is currently one of the major services that are developing at a rapid pace.4G (also known as beyond 3G) is a term used to describe the next complete evolution in wireless communications. A 4G system will be able to provide a comprehensive Internet Protocol solution where voice, data and streamed multimedia services can be provided to users on an "anytime, anywhere" basis, and at higher data rates than previous generations. This implies that roaming between different networks must be automatic and transparent to the user. The international telecommunications regulatory and standardization bodies are working for commercial deployment of 4G networks roughly in the 2012–2015 time scale.



## Introduction

Mobile communication is currently one of the major services that are developing at a rapid pace.4G (also known as beyond 3G) is a term used to describe the next complete evolution in wireless communications. A 4G system will be able to provide a comprehensive Internet Protocol solution where voice, data and streamed multimedia services can be provided to users on an "anytime, anywhere" basis, and at higher data rates than previous generations. This implies that roaming between different networks must be automatic and transparent to the user. The international telecommunications regulatory and standardization bodies are working for commercial deployment of 4G networks roughly in the 2012–2015 time scale. 4G will be capable of providing between 100 Mbps and 1 Gbps speeds both indoors and outdoors, with premium quality and high security. Presently Worldwide Interoperability for Microwave Access (WIMAX), Long Term Evolution (LTE) are the two contenders for 4G services.4G equipment will employ the Orthogonal Frequency Division Multiple Access(OFDMA) method,Multiple Input Multiple Output (MIMO) techniques for Space Division Multiplexing (SDM) or Smart Antenna.

## Smart Antenna

Future mobile communications systems are facing an increasing demand for heterogeneous broadband services and applications. Given the limited spectrum available to provide high data rate communication for an increasing number of cellular subscribers, it is generally expected that the deployment of smart antennas will increase the overall system capacity and performance. A smart antenna combines several antenna elements with a signal-processing capability to optimize its transmission and reception beam patterns automatically. Smart antenna technology offers a significantly improved solution to reduce interference levels and increase the link range and enable frequency reuse of the channels. With this technology, each user's signal is transmitted and received by the Base Station (BS) only in the direction of that particular user. This drastically reduces the link power budget as well as the overall interference in the system. The use of smart antenna technology enables service providers to extend range, increase Quality of Service and make more effective use of channel and bandwidth capacity for nearly every wireless communications technology. Features and Benefits of Smart Antenna Systems are: signal gain, better range, and interference rejection, increased capacity, spatial diversity multipath rejection, power efficiency, and reduced cost of services.

## Beam Forming Network (BFN):

Circuits that can perform beam steering as well as beam shaping are called Beam Forming Network (BFN). Beam forming network combine the antenna arrays with the signal processing to steer themselves automatically to pick out the signal in response to the direction of arrival and separate the signal from the direction of interference. A variety of functions such as beam steering, beam shaping, beam scraping, multibeam transmission can be done by beamforming network. Amplitude and phase of the signals are controlled by BFN separately according to signal distribution in the intended direction.

**Beam forming techniques for array antennas can be categorized into three types:**

1. RF (microwave or millimeter wave) beam forming
2. Digital beam forming
3. Optical beam forming

## RF beamforming technique

Figure 1.1. illustrates basic configuration of beam forming networks using RF technique assuming a multibeam transmitting array antenna that has M input beams and N output elements. RF beam forming is the most common technology, and is widely used in small scale systems (J.S.Ajioka, et al 1988). Typical matrix network type of them requires M x N components of phase shifters, attenuators and interconnections, which are used to control the phase and amplitude of the received signals and steer to the user direction. However, it has the drawback that as the antenna size is increased, circuitry structure becomes complex, cumbersome, and expensive hardware is required for large scale systems.

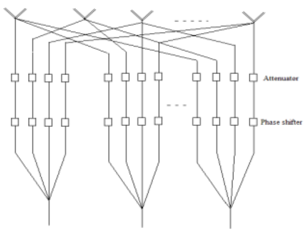


**Figure1.1. Basic Configuration of RF beamforming network**

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**Digital Beamforming Technique**

As for digital beam forming, signal processing is carried out in a digital signal format, in which highly flexible algorithms can be utilized to modify the received signal at the base station. The technology combines the inputs of multiple antennas to form very narrow beams towards individual users in the cell. Figure1.2. shows the digital beamforming network. In this technique received signals are digitally processed in parallel, and this method requires up/down converters (U/DC), analog to digital converters (A/D). However the speed of digital processor will limit the signal bandwidth within 100 MHz (T.Tanaka, et al, 1996).

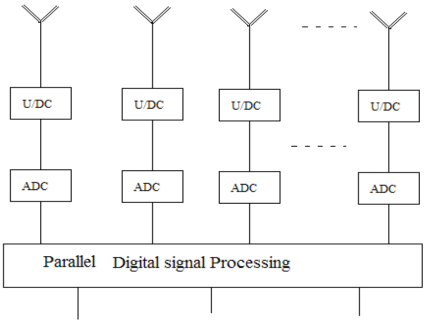



**Figure 1.2. Digital beamforming network**

**Optical Signal Processing Beamforming Technique**

Optical Signal Processing BeamForming Network (OSP-BFN) provides both signal distribution and processing function in optical domain. OSP (Optical Signal Processing) method can greatly reduce the complexity of the conventional system and increase the speed. The OSP-BFN itself is independent of RF frequency, because the optical frequency is by several times high compared to the RF frequency. As for optical component the advantages of wide bandwidth, low mass, small size and immunity to electromagnetic interferences are widely recognized. Moreover, due to its use of parallel signal processing, the number of hardware components is reduced from M x N which is required in the RF BFN to M+N.

The Basic configuration of OSPBFN multibeam system is composed of a Control Station/Central Station (CS), a several radio Base Stations (BS) and many personal mobile terminals as shown in figure 1.3. In this technique, the OSPBFN can process the optical signal directly sent from the CS. Especially in Pico cellular systems, a large number of BS are required which have to be simple in their design. These BSs are connected to a CS via optical fibers offering low loss and large bandwidth transmission properties.

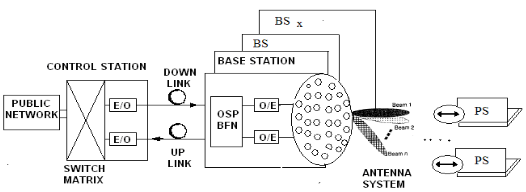



**Figure 1.3. Basic configuration of OSPBFN multibeam system [Inagaki,et al,1997]**

Therefore, it is remarkably compatible with an optical fiber subcarrier transmission system. Smart antennas installed at the BSs access to a number of PSs (Personal mobile Systems) by multiple spot beams. An OSP in a BFN generate desired amplitude and phase distribution for each array element by means of spatial parallel signal processing. Data corresponding to each beam directly modulate individual optical carrier at the control station. These up-converted optical signals are sent to the BS through the optical fiber. An optical reference carrier is also sent to BS through another fiber. Each modulated optical signal is processed with spatial-parallel conversion at BFN in the BS, then down converted to RF signals with the optical reference carrier by heterodyne technique .The multibeam antenna fed by the converted RF signals emit each beam to access individual personal mobile terminals.

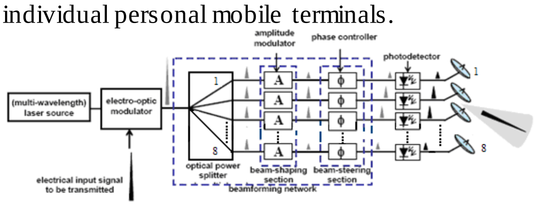



**Figure 1.4. Simplified schematic diagram of an OSPBFN for eight-antenna Elements**

The simplified schematic of OSPBFN is shown in Figure 1.4. The optically modulated input signal to be transmitted to the Base station is first divided by the number of antenna elements with an optical power splitter. Then, each of these signals is connected to amplitude controllers, which regulate the amplitude levels of each signal and eventually determine the shape of the transmitted beam (i.e. the beam width of the main lobe, and the power levels of the side lobes). This operation is called beam shaping. Beam shaping is achieved by controlling the amplitude of the optical signal applied to each antenna element. In practice, this is done via optical attenuators. Afterwards, each of the amplitude controlled signals is connected to an optical phase shifter, which regulates the phase of each signal and sets the direction of the transmitted beam. The differential phase delay determines the direction of the transmitted signal. This operation is called beam steering. Finally, the individual controlled signals are applied to their respective element after down conversion to electrical signal by photo detector and transmitted out towards the end-user. A brief review of the current status of the OSPBFN is presented here.

**FT lens Based OSPBFN**

The functional block diagram of the optical feed for a multibeam microwave array antenna is shown in Figure 1.5. Fourier transform (FT) lens is used as the main component in this optical processor (T.Akiyama, t al 2001). The reason for this arrangement is that the far field radiation pattern of a microwave array antenna is the FT of its aperture distribution, and the amplitude and phase distribution on the aperture are excited by the RF beat signal of two laser beam on the optical fiber array input plane which is the image focal plane of FT lens, therefore the desired antenna pattern will be achieved by the scaled illumination mask pattern in the object focal plane of FT lens.

The 'n' optical fibers connecting to different master lasers are placed in the input focal plane of the FT lens, and their center is $r_0$ from the optical axis. The emitting optical beams from the fibers will be Gaussian distribution beams. After transmitting to the FT lens, the beams will focus in the image plane with the same Gaussian intensity and different phase distributions.

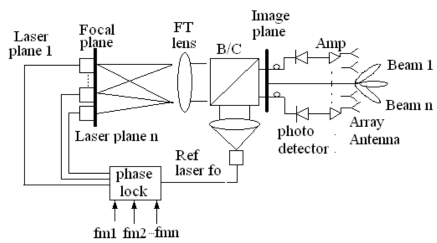



**Figure 1.5. Schematic of FT lens OSPBFN**

The optical beams from the master lasers and the reference laser are mixed at Beam Combiner (B/C) and are incident on a sampling fiber array placed in the image focal plane of the FT lens, so the frequency differences between optical beams from the master lasers and the reference laser as RF beat note signals will be detected by a photo detector and fed to the radiating elements of a microwave array. Gain degradation of 3.8dB was observed.

**True time delay Based OSPBFN**

The optical beam forming (B.Vidal,et al 2002) architecture shown in fig 1.6 is based on intensity modulation and direct detection, using 40 GHz Mach-Zehnder modulators for both transmission and reception. The beam forming is achieved by using a multi wavelength laser in combination with a digital delay line based on a fast InP based switch matrix and dispersive fibers. This architecture is based on using different simultaneous optical wavelengths with wavelength dependent optical delay lines that introduce relative delays among the different wavelengths due to optical path dispersion. An optical wavelength-to-array element correspondence is established, so it is only needed to separate each wavelength toward its corresponding antenna. Transmission and reception paths use the same beam forming circuit which is hence needed only once.

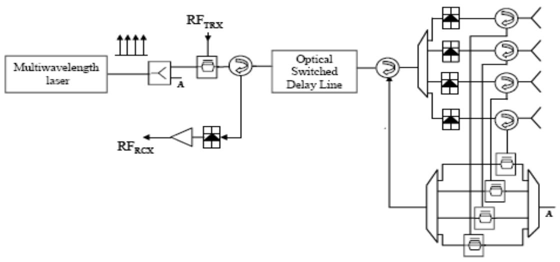



**Figure. 1.6. Optical beamformer architecture**

The most obvious advantage of using WDM delay lines to implement time delays is that it allows generating all the time delays for the entire array using only one switched delay line as shown in figure 1.7. Moreover, due to the optical wavelength-to array element correspondence, there is no splitting loss associated with signal distribution to array elements. The envisaged scenario for the broad band wide access network is based on a squared cellular pattern with certain overlap and four 90 degrees sector per squared cellular cell .The duplexing approach is TDD and the multiple access method is TDMA(Time Division Multiple Access) which presents inherent benefits for highly asymmetric data services. To introduce beam forming in these networks, a space-switched single-beam antenna covering the whole sector is used instead of the traditional sectorial antenna. Major weakness of this method was requirement of long fibers (in m & km) and narrow scanning sector (+22º to -20º).

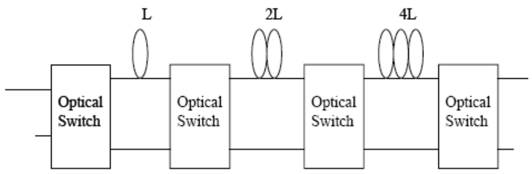



**Figure. 1.7. Optical binary switched delay line.**

**Dispersive prism Based OSPBFN**

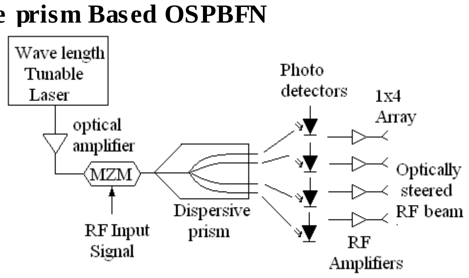



**Figure 1.8. Schematic of prism based OSPBFN**

A schematic of the transmit (S.Blanc,et al 2003) array beam forming system is shown in fig 1.8. The main beam former is based on the fiber optic dispersive prism approach and provides a wavelengths-dependent time delay at each array element proportional to the position of the corresponding element in the array. This is accomplished via an optical-dispersion gradient in the beam former. Hence, by tuning the wavelength of the laser, the dispersion gradient is translated into a time-delay gradient at the antenna element output, producing a time steered far-field pattern. An external-cavity single-mode semiconductor laser, which is tunable across a wavelength range of 1470-1590 nm as the optical source for the system. The 1.5mW output of the laser is amplified to 75mW by an Erbium-Doped Fiber Amplifier (EDFA) and is subsequently modulated by a commercially available Mach-Zehnder modulator (MZM) capable of intensity modulation upwards of 40 GHz. A 0.05 -590 GHz preamplifier, with a nominal gain of 30 dB and a saturated output power of 10mW is used at the RF input of the MZM to ensure adequate dynamic range at the MZM and to overcome the inherently high RF loss in the microwave cables feeding the system.

The modulated optical carrier is then split and fed into the four-channel fiber-optic dispersive prism. The nominal unit length of high-dispersion (HD) fiber (ps/nm km) in the prism is 25m. Thus, the four links have 0, 25, 50, and 75 m of HD fiber, respectively. The total length of HD fiber in each link of the prism is known to within 22 cm. The overall link lengths are equalized with dispersion-shifted (DS) fiber such that the total difference in the optical time delay between any two links, at the center wavelength (1555 nm), is less than 2ps. Final time trimming is accomplished by adjustment of the fiber-optic stretcher present in each link. The stretchers have a resolution better than 0.25ps (3.6 at 40 GHz) and exhibit no microwave phase dispersion across the frequency band. Each fiber optic link also includes a fiber optic attenuator (FOA) for microwave frequency independent amplitude matching.

The optical signal is then demodulated by a commercially available 50 GHz p-i-n photodiode (PD).The nonterminated microwave output of the PD is passed through a 6-dB attenuator and then a 60GHz bias tee, which reduce microwave back-reflections while allowing for voltage biasing of the PDs. The signal is then amplified by broad band 10-40 GHz low noise amplifiers (LNAs) having nominal gains of 35 dB, at the low end of the frequency range. The outputs of the four LNAs are connected to every other element of a 1x8 waveguide antenna array. Total radiated output power for the system was less than 10mW. The following drawbacks were mentioned in this method. The phase tracking error was 6.6% and the amplitude error was 25%. Scanning sector covered +60º to -60º.

**PDM based OSPBFN**

(S.Grinari, 2003)Modulation of multiplexed channels ensures zero phase delay between the RF signals before the optical carriers are processed. The RF signals modulated on the even and odd channels are in phase. The modulated optical carriers feed the PDM, which performs the true-time delay processing. The PDM is capable of providing independent

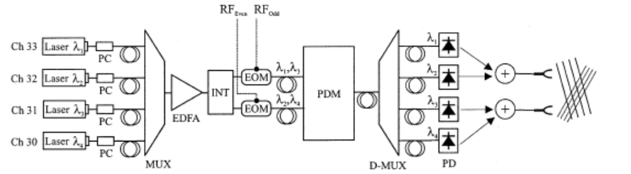



**Figure.1.9. Two-beam two-channel optical beamformer.**

Time delays for the even and odd channels. For each configuration of the PDM, λ4 lags λ1 and λ2 lags λ3 by an independent time period. At the output of the PDM, after the proper phase difference is set, optical signals are demultiplexed. Four broad-band photodetectors, in a direct detection configuration, recover the processed RF signals. Then the RF

**Table. 1.1 Overall comparison of different OSPBFN architectures:**

| **OSPBFN architectures /Tx&Rx modes** | **Phase control/amplitude control methods** | **Deviation in LD/NDs from theoretical values** | **Scanning Sector (°)** | **HPBW Of Main lobe** | **Average side lobe level** | **Drawback** |
|---|---|---|---|---|---|---|
| T.Akiyama et al 2001,2000 – Both TX /RX | GIF lens | LD deviation 4.5% | -30 to +30 | 20 ° | -12 dB to -30dB | 1. Optical loss high due to the imperfect alignment of GIF lens. 2. LD error is considerable. 3.Scanning sector is moderate . |
| S.Granieri, 2003. Both TX &RX | Only phase control -TTD-PDM | LD Deviation 9.3% | 0 to 69 | 31° | Side lobe is not specified. | 1. Requires many optical sources. 2.LD error is high 3. NDs are not taken care of. 4. Main lobe is quite broad. |
| B.Vidal,2002,2006 Both TX &RX | Only phase control -notch filter and switch matrix | Not available | -22 to +22 | 20 ° | -17dB & | 1.Requires SMF of length 1km & 5km 2. Scanning sector is small. |
| Lluís Jofre, 2008 TX only | VOA & PALSLM | LD Deviation 6% | -20 to +20 | 17 ° | -11dB | 1. Amplitude – frequency dispersion produced by PAL-SLM &VOA. 2. Scanning sector is very small. 3. Side lobe suppression is not satisfactory. |
| H.Shippers et al 2008,2009 Both TX &RX | Optical Ring Resonator(ORR) | Not available | 0 to 90 | Not available | Not available | 1. 1 x8 OSPBFN requires 31 heaters with total power of 8W. 2.LD/ND are not reported |
| Byung-Min Jung,et al 2009-TX only | Only phase control (Fiber Bragg Grating Prism -azimuth beam steering& Switch-based Fiber-Optic Delay Lines - elevation beam steering) | LD deviation 6.3% | -24 to +24(azimuth angle ) 0 to 40 (Elevation angle ) | Not available | Not available | 1.Scan sector is small 2. LD error is considerable. 3. Null Directions are not taken care of. |
| M.Y.Chen et al 2008,2009 Both TX/RX | Only phase control -Photonic crystal fiber | LD error is small.(Not specified) | +45 to -45 | 55 ° | Side lobe is not specified. | 1.Requires PCF of length 10.5m 2. NDs are not taken care of. 3. Main lobe is very broad |
| Caroline.P.E,A. P.Kabilan, 2005,2008,2011 , | Both phase control and amplitude control | LD-deviation 0.7% | +60--60 | 15 ° | -20.5 | 60cm $PVF_2$ coated SMF is required |
| Caroline.P.E,A. P.Kabilan 2006,2010 | | 1.3% | +60--60 | 14.8 ° | -21 | MEMS-OSPBFN may be implemented in an integrated optical chip |

signals are linearly combined and amplified before feeding the antenna T/R elements.

This method required many optical sources. The disadvantages of this method were: switched delay lines caused high side lobe levels in the radiation pattern of the antenna array; needed a complex switching network; HPBW of the main lobe was 31º; LD error was 9.3%; NDs were not taken care of and main lobe was quite broad.

**PAL-SLM based OSPBFN:**

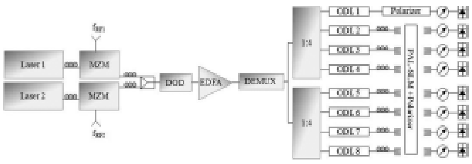


**Figure. 1.10. Block diagram of a two-beam optical beamforming network for controlling an 8-subarray antenna.**

This OBFN architecture shown in fig.1.10, (Lluís Jofre,et al 2008) is based on providing to the different subarrays time-delays introduced by fiber-optic delay lines (ODLs) and phase-shifts produced by a parallel-alignment spatial light modulator (PAL-SLM). Basically, two CW-lasers are amplitude modulated using a dual-drive MZI to generate SSB modulation and amplified by an Erbium Doped Fibre Amplifier (EDFA) and launched to a DGD module, which cross polarizes the optical carriers and the sidebands. Next, the signals are demultiplexed using an add-drop multiplexer that routes the two different wavelength channels from the same data stream to two different paths, consisting on two 1 x4 fibre-optic couplers/splitters. From each coupler, the signal is split into four channels wherein the time delays at subarray level are adjusted by means of optical delay lines (ODL). Next, the signals are launched to free-space by fiber collimators, where a PAL-SLM is used to control the phase-shift of every pixel element. After the PAL-SLM, a polarizer is needed to combine, in a single polarization state, the optical carrier and the sideband; otherwise no signal will be detected at the photodiodes. Finally, the optical signals are detected through photodiodes that converts them back to RF and transmitted through antenna.

This architecture had the drawbacks of high LD error (6%), small scanning sector (-20º to +20º) and unsatisfactory side lobe suppression.

**Photonic Crystal Fiber Based OSPBFN**

Figure.1.11. shows a schematic of the operation principle for optical beamformer architecture with an arbitrary number (M) of wavelengths feeding an N -element array antenna (Chen et al 2008, Subbaraman et al 2008). For a single RF beam generation, only one tunable laser is presented to provide optical carrier with wavelength $\lambda$ . Then it will be modulated with

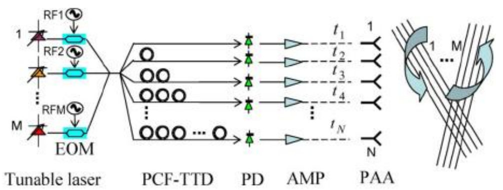



**Figure.1.11. Multibeam transmitter architecture ; PAA, photonic crystal fiber (PCF), true-time delay (TTD).**

RF signals using an electro-optic modulator (EOM). The modulated optical carrier feeds the PCF-based TTD module. The TTD module is to provide time delay for N-element PAA such that the steering angle can be continuously tuned by tuning the wavelength of the laser. After the pre-designated time delay within the delay modules, the optical signals are converted into the corresponding electrical signals by N photo detectors. The electrical signals are then fed to the phased array antenna. The negative aspects of these methods were listed as: LD error was small (Not specified). The scanning sector was +45º to -45º; This method required PCF of length 10.5m; NDs were neglected; HPBW of the main lobe was 55º and Main lobe was very broad.

**2D Optical True Time-Delay (TTD) Beamformer:**

2-D optical TTD beamforming system for p x q a PAA is shown in Fig.1.12.The system (Byung-Min Jung,et al 2009) consists of a multiwavelength source with p-wavelengths, a wavelength-dvision-multiplexing (WDM) multiplexer (Mux), an electrooptic modulator (EOM), an erbium-doped fiber amplifier (EDFA), a 2-D TTD consisting of a WD-TTD(Wavelength Dependent) and a WI-TTD(Wavelength Independent), q WDM demultiplexers (Demuxs),and p x q photodetectors. The p wavelengths from the multiwavelength source are multiplexed at the Mux, and modulated by the radio-frequency (RF) signal at the EOM. The modulated optical signal carried by the p wavelengths is amplified by the EDFA and then applied to the 2-D optical TTD to obtain wavelength-dependent and wavelength-independent time-delays. Specifically, in the WD-TTD the RF signals carried by wavelengths are reflected by the FBGs (Fiber Bragg Grating) at different locations, generating time-delays for azimuth beam steering .The time-delays for elevation beam steering are generated by the WI-TTD .The q delay lines at the output of the WI-TTD are connected to q WDM demultiplexers, with the optical signal from each delay line being split into p-wavelength channels and then fed to a PAA with p x q antenna elements. The snag of this methods were high LD error (6.3%), narrow scanning sector (-24º to +24º in azimuth and 0 to 40º in elevation) and negligence of NDS.

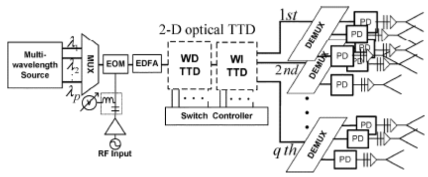



**Figure. 1.12. Schematic diagram of the 2-D optical TTD beamforming system**

**Optical Ring Resonator based OSPBFN**

A complete optical beam forming system consists of optical modulation, optical signal processing, and optical detection. The core section is the optical signal processing which is performed by an OBFN(L.Zhuang, , et al, 2006,2007). Here OSPBFN is a complete system using an ORR-based OBFN, filter-based optical SSBSC modulation, and balanced coherent detection. The system architecture is shown in Fig. 1.13.

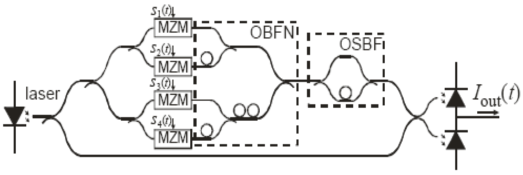



**Figure 1.13. Schematic of the ring resonator-based optical beam forming system (MZM: Mach-Zehnder modulator, OBFN: optical beam forming network, OSBF: optical sideband filter).**

The number of cascaded ORRs is different in each stage, so that an increasing number of cascaded ORRs are connected from output 1 to output 8, to meet the delay requirements for beam forming. The number of outputs of the OBFN can be extended by simply adding more stages. The tunability of the splitters provides the opportunity to specify different amplitudes for different outputs, which enables antenna side lobe suppress. However the currently developed ORRs suffered from two major drawbacks: 1) The coupling factors were adjusted manually 2) 1x8 OSPBFN required 31 heaters with total power of 8W .Hence if coupled ORRs were to be used in PAA, an automatic fast method to adjust the coupling factors was necessary.

**Inverse Piezo Electric Effect -OSPBFN**

The functional block diagram of OSPBFN(Caroline et al 2005,Kabilan et al 2010) is shown in Figure 1.14. The optical signal of one user with carrier wavelength of 1.55 µm is split up into eight signals by using 1x8 power splitter. These signals are fed to the $PVF_2$ coated optical fibers for phase control. The IPEE of the $PVF_2$ coated fiber is exploited to achieve optical phase shifting. When a sinusoidal voltage of 500 KHz with value ranging from 0-30V is applied to the coated fiber, the strain produced in the fiber changes the phase of the optical signal from 0º to 180º.

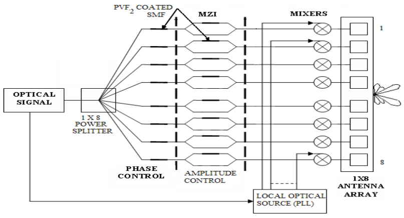
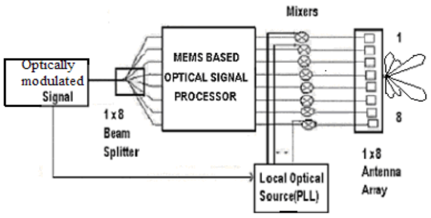



**Figure 1.14 Proposed OSPBFN using coated SMF arrays**

Amplitude control is accomplished by MZI. Phase controlled optical signals are fed to the MZI in which one of the arm is coated with $PVF_2$ and the other is the reference arm. Again the IPEE is used to achieve the desired phase shift within the MZI section so that an amplitude change is produced at the output. The results obtained from the simulation are as follows: Look Direction (LD) and Null Directions (NDs) of the radiation pattern deviate by not more than 0.7%, from those of the desired pattern .The main lobe to total power ratio is about 3.9:5. The Half Power Beam Width (HPBW) of main lobe is around 15º. The average side lobe level is -21dB and the average null level is -42dB.

**1.3.3.9 Micro Electro Mechanical System(MEMS) Based – OSPBFN**

This design is based on a microelectro mechanical system (MEMS) as shown in fig.1.15(Kabilan et al 2006,2011). The phase and amplitude of the signal fed to each antenna element is controlled by a pair of micromirrors placed at 90° to each other and each are driven by a parallel plate electrostatic actuator in one method and by a comb drive electrostatic actuator in another method. The optically processed signals are heterodyned with the signals from a phase locked local optical source to obtain 2GHz RF signals. The weighted RF signals are fed to a 1x8 patch antenna array .The results are as follows: LD and NDs deviate by not more than 1.3% from the desired values, main lobe to total power ratio is 3.9:5, HPBW of main lobe is around 15º, average side lobe level is -21dB and average null level is -42dB.




**Performance Comparison Between The Different Existing Ospbfn**

The performance comparison between the different existing OSPBFN methods is presented in Table 1.1.

**Conclusion**

The above mentioned architectures show the various fields of optics that have been reviewed to realize beamformers, which are: fiber optics as ODL, fourier optics, integrated optics, spatial light modulation, and WDM. Examples of a few recent concepts are: dispersive photonic-crystal fibers, and Fiber Bragg Grating Prism and optical ring resonators. While comparing the deviation in LD with the above mentioned architectures, only PCF based method agrees very well with the theoretical LD. The beam steering direction error (9.3%) is the highest for the architecture given by S.Granieri, 2003.The scanning sector for all the above mentioned references are significantly less. The beamforming architecture given by Lluís Jofre, 2008 & 2006 yields best HPBW compared to other architectures. Side lobe suppression is not satisfactory except the architecture given by T.Akiyama et al 2001, 2000. The performance of the Inverse Piezo Electric Effect-OSPBFN is slightly superior to the MEMS-OSPBFN, the cost of fabrication of the former is likely to be higher due to relatively expensive MZI. Furthermore, the OSP portion of MEMS-OSPBFN may be implemented in an integrated optical chip using a conventional IC technology.

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