A Novel 2N Beams Heterodyne Optical Beamforming Architecture based on NxN Optical Butler Matrices

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Abstract **— A novel beamforming architecture based on optical Butler matrices is proposed and experimentally evaluated. The optical Butler matrix operating principle and the effects of fabrication inaccuracies on the beamformer radiation pattern are presented. The proposed architecture offers simultaneous multibeam generation capability. 40 GHz RF phase measurements are presented with low ripple and high linearity. Finally, an upgraded architecture is proposed which allows to double the number of beams (2N).**

I. INTRODUCTION

During the last years, lots of research efforts have been dedicated to the use of optical beamforming techniques for phased-array antennas [1]-[4] due to their low-loss, reduced weight, no susceptibility to electromagnetic interference or wide instantaneous bandwidth features. However, the high cost of optical beamformers has limited its application mainly to defense applications.

For wide bandwidth applications, true time delay (TTD) is required, as opposed to simple phase shift, to prevent beam squint. Among phase control architectures, the most widely investigated are those based in heterodyne systems, where induced optical phase shift are translated to the electrical domain. Several methods to control the optical signal phase have been proposed during last years, such as acoustically driven integrated optical circuits, bulk liquid-crystals or thermo-optical and electro-optical devices. Another possible solution is the use of fixed phase shift networks, such as Butler and Blass matrices.

Optical Blass matrices provide TTD within heterodyne systems and have been reported in [5]. On the other hand, optical Butler matrices have been theoretical proposed as part of a beamforming network [6] and experimentally proved as an angle-of-arrival estimator [7].

In this paper, a beamforming network based on optical Butler matrices (BM) is proposed. An analysis of the impact of BM fabrication inaccuracies and their impact on the beamformer performance has been carried out. A novel upgraded architecture based on the BM which doubles the number of generated beams is proposed

Finally, measurements of the delay profile around 40 GHz are provided, which show very good linearity and low ripple.

II. OPTICAL BUTLER MATRIX THEORY

BM have been mainly used as multi-beam electrical beamforming networks for linear antenna arrays although similar structures may be used for planar arrays [8]. A standard BM is a N × N network where N is the number of input/output ports [9]. N is required to be a power of 2, i.e. $N=2^n$ where n is an integer.

The electrical BM consists of a number of rows of hybrids, interconnected by rows of fixed phase shifters. When a signal impinges an input port produces a different inter-element phase shift between the output ports. The set of different inter-element phase shift is given by:

$$\Delta\phi = \pm(2k-1)\frac{\pi}{2N} \qquad k \in [1, N] \qquad (1)$$

where N is the number of ports of the matrix. If the output ports are connected to a linear array of radiating elements, that phase shift causes a deflection of the beam from the broadside position. Thus, an optical signal impinging an input port produces a beam at a certain angle and therefore N different beams may be obtained simultaneously.

The same principle used for the design of microwave BM may be extended to optical frequencies as long as equivalent building blocks (90° or 180° 3dB couplers and fixed phase shifters) are found. A standard 3 dB optical coupler behaves as a 90° hybrid and a fixed length of fiber or optical waveguide introduces a given phase shift. BM are specially indicated for optical integration, as a more accurate control of waveguide lengths may be realized improving the precision of the desired inter-element phase shifts of the final device.

Microwave BM consisting of fixed phase shifters and hybrids couplers have poor performance because of the high crosstalk and electromagnetic interference (EMI) [10] when a high number of ports are needed. Integrated optical BM, in addition to being immune to EMI and having negligible crosstalk (for instance, two optical channel waveguides intersecting at an angle of 3.3° have roughly – 15 dB crosstalk and at angles around 10° the crosstalk is negligible [6]), are small in size, lightweight and may be manufactured on a single substrate.

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Though those advantages, optical heterodyne systems are very sensitive to optical phase drifts. As the architecture based in the Butler matrix is an heterodyne system, the Butler matrix has to be fabricated very accurately.

III. ARCHITECTURE DESCRIPTION

The architecture here presented was first suggested in [6]. Fig. 1 shows a first beamforming network approach for the downlink. A dual optical source is used to obtain two correlated optical signals (one of them is modulated by downlink data) with a frequency difference of f_{RF}, where f_{RF} is the desired RF signal frequency which is generated by the heterodyning of those signals in the photodiode. Those signals are transmitted through a fiber link to the base station (BS), where the beamformer and the antenna array are placed.

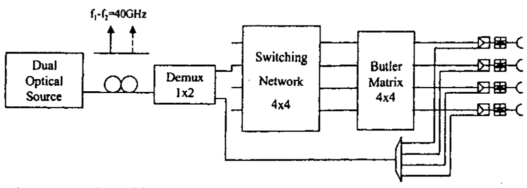

Fig. 1. Simplified downlink proposed scheme.

Then, the two optical signals are split with a wavelength demultiplexer so that one of them passes through the BM while the other one goes directly to the photodiode array. At the BM output, N optical modulated signals with the same amplitude and different phases are obtained, N being the number of ports of the matrix,. After heterodyning, N electrical signals with frequency f_{RF} and a fixed inter-element phase shift are obtained at the antenna array. There are as many possible fixed beams as input ports the used matrix has. In order to switch the generated beam, the signal has to be input to the BM at different ports.

In order to choose the beam, that is to say, to select the matrix input port, a first approach is to have a switching network before the BM input ports, as depicted in Fig. 1.

For the reception mode, the proposed system set-up is very similar. Now, N local oscillator signals are obtained at the beam-former output with proper phase difference in order to carry out the electrical down-conversion of the signals received from the antenna array.

It should be pointed out that BM performance is frequency independent, i.e., with the same design, the same inter-element phase shifts are obtained for different electrical frequencies. However, when broadband signal are considered this beamforming architecture suffers from the beam squint effect, as no delay but phase control is performed.

IV. SENSITIVITY ANALYSIS

Once the basic architecture has been presented, its sensitivity to fabrication errors of the BM is studied. For the analysis, an optical signal impinges one input of the BM and the amplitude and phase variance at the matrix outputs are calculated as a function of four possible error sources as defined in [10]:

- Coupler amplitude imbalance: both outputs of each coupler may not have the same amplitude.
- Coupler additional losses: the insertion losses for all couplers are not the same.
- Coupler phase imbalance: insertion phases in each coupler path are not 0° and 90° respectively.
- Fixed phase shifter errors.

In all the simulations, the errors for each element have been assumed to be independent but with similar statistics (Gaussian distribution with zero mean). Monte Carlo simulations of a 4×4 and 16x16 BM have been carried out in order to determine how sensitive would the beamformer be to those fabrication parameter uncertainties.

TABLE I
ARRAY PATTERN DEGRADATION AS A FUNCTION OF COUPLER AMPLITUDE IMBALANCE.

Amplitude imbalance standard deviation (dB)	Output normalized amplitude variance		Residual sidelobe level (dB)		Directivity degradation (dB)	
	4x4	16x16	4x4	16x16	4x4	16x16
0.5	0.001	0.003	-33.97	-36.83	0.006	0.014
1.5	0.014	0.029	-24.55	-27.39	0.060	0.124
2.5	0.035	0.072	-20.57	-23.44	0.149	0.301
3.5	0.063	0.132	-18.02	-20.81	0.265	0.538

Once the amplitude and phase variances at the output ports of the optical BM have been calculated, the effect of these errors on the array pattern has to be studied. The relationship between the amplitude and phase variance and the directivity and a residual side-lobe level yield [8]:

$$\overline{\sigma^2} \approx \frac{1+\overline{\Delta^2}+\overline{\delta^2}}{N} \qquad (2)$$

$$\frac{D}{D_0} \approx \frac{1}{1+\overline{\Delta^2}+\overline{\delta^2}} \qquad (3)$$

where $\overline{\sigma^2}$ is the residual sidelobe level, and $\overline{\Delta^2}$ and $\overline{\delta^2}$ are the variances of amplitude and phase errors. Eqns. (2) and (3) are obtained assuming that the amplitude and phase errors follow a Gaussian distribution with zero mean. Tables I to IV summarize the simulation results obtained for the directivity and residual side-lobe level variation as a function of the abovementioned sources of error. Results show that the BM should be fabricated accurately to avoid high variances in the array pattern.

TABLE II

ARRAY PATTERN DEGRADATION AS A FUNCTION OF COUPLER LOSSES.

Losses standard deviation (dB)	Output normalized amplitude variance		Residual sidelobe level (dB)		Directivity degradation (dB)	
	4x4	16x16	4x4	16x16	4x4	16x16
0.25	1.9e-3	3.2e-3	-33.3	-36.90	0.008	0.014
0.5	3.4e-3	9.1e-3	-30.71	-32.43	0.014	0.039
0.75	5e-3	0.014	-29.03	-30.59	0.149	0.060
1	6.3e-3	0.017	-18.02	-29.67	0.265	0.074

TABLE III

ARRAY PATTERN DEGRADATION AS A FUNCTION OF COUPLER PATH IMBALANCE.

Phase error standard deviation (degrees)	Output phase variance (rad)		Residual sidelobe level (dB)		Directivity degradation (dB)	
	4x4	16x16	4x4	16x16	4x4	16x16
5	0.015	0.03	-24.26	-27.25	0.06	0.13
15	0.135	0.275	-14.72	-17.63	0.55	1.06
25	0.38	0.76	-10.22	-13.21	1.4	2.46
35	0.76	1.42	-7.21	-10.50	2.7	3.84

TABLE IV

ARRAY PATTERN DEGRADATION AS A FUNCTION OF FIXED PHASE SHIFTERS PHASE ERROR.

Phase error standard deviation (degrees)	Output normalized amplitude variance		Residual sidelobe level (dB)		Directivity degradation (dB)	
	4x4	16x16	4x4	16x16	4x4	16x16
5	0.008	0.024	-26.99	-28.22	0.034	0.10
15	0.067	0.201	-17.76	-18.99	0.281	0.8
25	0.194	0.6	-13.14	-14.24	0.149	2.04
35	0.36	1.09	-10.46	-11.64	0.265	3.20

V. UPGRADED ARCHITECTURE PROPOSAL

In this section, an upgraded beamforming architecture which uses BM is proposed. In the scheme shown in Fig. 1, the two correlated optical signals arriving at the BS are separated, one travels through the matrix experiencing the corresponding phase shifts while the other directly passes to the photodiodes array. If that signal also enters the BM, it also experiences a phase shift in such a way that after heterodyning, N signals with frequencies and phases equal to the difference between frequencies and phases of the two optical signals are obtained.

Therefore, if that second signal is injected into the first input port, using for instance a 4×4 Butler matrix, 0°, ±45°, ±90°, ±135° and 180° phase shifts are obtained, besides the traditional ±45° and ±135° phase shifts. To achieve this feature, the only variation on the basic structure consists on including a 1×2 switch and a 1×2 coupler in front of one input port, for instance, at input 1.

VI. EXPERIMENTAL RESULTS

As a first approach to proof the concept of an optical beamformer based on an optical Butler matrix, the following measurements have been carried out. Fig. 2 depicts the measurement set-up. The 2 x 2 optical Butler matrix is made of one 3dB optical coupler and some fixed optical phase shifters. Due to current equipment limitations, instead of an heterodyne millimeter wave generation scheme, an electro-optical amplitude Mach-Zehnder modulator (MZM) was used. Therefore, a 16dBm 40 GHz signal was used to externally modulate an optical wavelength. Due to the 13 GHz MZM bandwidth, a low optical modulation index was achieved at the MZM output. After the amplitude modulation stage, three optical signals were obtained with 40 GHz spacing. Before separating them, one of the optical carriers was filtered using a dichroic filter. Then, two optical signals separated 40 GHz are obtained, they were further separated using a fiber grating filter acting simultaneously in the transmission and reflection mode as shown in Fig. 2. After separating them, only one optical carrier passes through the BM before they get combined again before the photodiode. Then, the phase difference between input RF and output RF signals was measured using a HP8510C Network Analyzer for each input and output port of the optical BM. Fig. 3(a) shows the measured phase difference between the two output ports (corresponding to the two array elements) when the optical carrier is entered at port 2 of the matrix shown in Fig. 3(b).

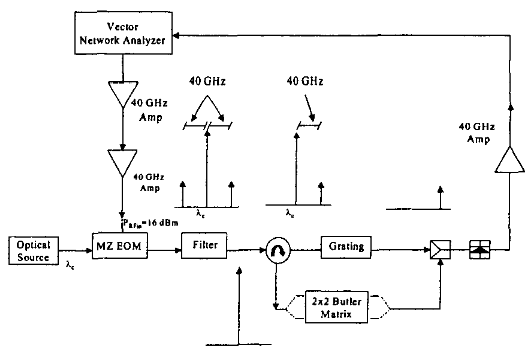

Fig. 2. Experimental set-up to characterize the optical beamformer based on an optical Butler matrix.

According to the measurements shown in Fig. 3(a) the phase difference between the 40 GHz signals detected at both outputs of the optical BM is 121.6 degrees when theoretical value is 90 degrees. This phase difference is kept for all the bandwidth considered, which is one of the main features of this beamforming proposal. This fixed difference between the measurements and the theoretical value is due to different lengths of the output fiber links (L_3, L_4) at each port of the optical 3dB coupler as shown in Fig. 3(b). After compensating this fixed phase difference, the standard deviation around this value would be the more important parameter. If the root mean squared error of the phase difference is estimated around the 121.6 degree value, the result will be σ=2.68 degrees which is almost the precision of a 6 bit switched line phase shifter.

Those fixed phase differences may be adjusted using fiber stretchers at matrix outputs as proposed in [7]. It is also important to point out that the highest potential of the Butler matrix is to be integrated in such a way that the smaller and more accurately controlled dimensions of the integrated device would reduce this dependence on optical path dimensions.

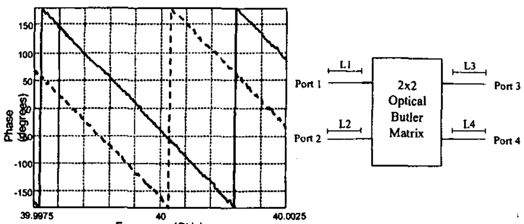

Fig. 3. Relative phase measurement for the two outputs (ports 3 (dashed) and 4(solid)) of the 2×2 optical BM when the signal impinges port 2 (left). Optical BM set-up (right).

These results may be calibrated using the fact that the undesired phase shift between the two signals to be beaten at each photodiode depends on the RF frequency but not on the optical frequency [11]. This way, the phase error may be easily estimated. If both optical signals are injected by the same input port, the theoretical inter-element phase shift is 0°. So, if both signals enter by input port 1 and 2, respectively, the inter-element phase shift should be the same but with the same RF path length error on both cases. Once the RF phase error is known (115° aprox, σ=1.66 and 1.69 degrees respectively), the measurements depicted in Fig. 3 may be calibrated. The measured phase shift value is 100° but, if the above mentioned path error is considered, the real value would be 215° (σ=1.77 degrees), that agree with the theoretical value of 180° except for the expected coupler error.

VII. Conclusion

An optical beamforming architecture based on optical Butler matrices has been presented and experimentally demonstrated. A sensitivity analysis of the impact of BM fabrication errors on the array parameters has been carried out. The experimental results show good performance though a more accurate control of fiber coupler and output fiber lengths is required to achieve good match with theoretical predictions. Finally, a novel architecture has been proposed which has frequency independent operation and easy multiple-beam generation capabilities (2N beams in front of the usual N beams achieved by traditional BM architectures). This architecture shows a good potential for optical integration.

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