PHOTONIC INTEGRATION FOR PHASED-ARRAY APPLICATIONS

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ABSTRACT

The use of photonics for phased-array applications has been discussed for quite some time. Main difficulties up to now have been the component count and cost for relatively complex systems. The advances in photonic integration are very promising to bring down both, as well as reduce volume and weight of phased-array beamforming networks as compared to their electrical counterparts. In addition, photonics allows for increased functionality for wide-bandwidth systems. This paper reports on these advances and indicates the strategy to applicable photonic phased-arrays.

INTRODUCTION

Phased-array antennas are in widespread use since the beginning of the 70's and are now becoming increasingly important for radar applications and in satellite and mobile communications. Phased-array antennas have the advantage of 2-dimensional scanning without moving mechanical parts, accurate beampointing, and phase and amplitude control to reduce sidelobes in the overall antenna pattern.

The use of photonics in phased-arrays has been discussed for quite some time. Main difficulties up to now have been the component count and cost for relatively complex systems. The advances in photonic integration are very promising to bring down both, as well as reduce volume and weight of phased-array beamforming networks as compared to their electrical counterparts.

In addition, photonics enables the use of antenna remoting and optical signal processing. Using a coherent detection scheme, phase and amplitude of an optical signal can be directly transferred to a microwave signal. In this way modulation of phase and amplitude of a microwave signal can be performed using optical phase and amplitude modulators. Also, advanced optical materials may be used for this signal processing.

Another advantage of the optical approach is the huge bandwidth which it offers: the response is flat from DC to tens of GHz. It is limited by the bandwidth of the photodetectors that can extend over 100 GHz. Other advantages of using photonics are the frequency independent low loss of optical fibres in comparison with coax cables, the insensitivity to electromagnetic interference (EMI) and the possibility of incorporating long true time delays, enabling large instantaneous bandwidth radar systems as well as very large antennas.

In this paper the integrated components available for this application will be discussed. The applicability will be illustrated by several examples using recently developed photonic integrated circuits.

INTEGRATED SIGNAL ROUTING

The most elementary function that can be performed by photonic integrated components is the routing of light. To that end, both splitters and switches are needed. For splitters, Y-branch splitters or MMI-couplers are available. The latter are smaller and provide more flexibility in splitting ratios, resulting

generally in a very compact element [1]. Switches can be realised using structures like directional couplers, Mach-Zehnder interferometers and asymmetrical Y-branches in case of digital switching.
Switching is performed either on basis of the thermo-optic effect, for example for polymer and silica switches and on the basis of the electro-optic effect for optically active materials such as InP and $LiNbO_3$. The thermo-optic effect is the slower of the two and switching times in the order of milli-seconds are typical. It depends on the phased-array application whether this switching speed is acceptable.
The on-off extinction ratio is currently limited for all types of switches, to somewhat more than 20 dB. An improvement in this ratio together with a decrease in the optical loss, currently of the order of a few dB, is needed.

INTEGRATED TIME DELAYS

Time delays can obviously be easily realised by lengths of fibre. The need for cutting the fibre accurately as well as their size favours the realisation [illegible] wavelength division multiplexing (WDM). This opens the possibility to use very hardware-compressive architectures for beamforming. The demultiplexing of these light colours must be performed at a certain place of the feed network to ensure that only the right colour feeds the antenna elements. This demultiplexing can be performed using compact integrated optic phasars or Bragg gratings [4].
Two options for beamforming are available with these components. The first is time-delay with dispersive fibers. This is not very suitable for integration, since the dispersion is usually too weak to allow for a small length of fibre. The second is to use a phasar with non-dispersive fibres, in a way similar as was previously proposed for prisms [5]. This approach is very suitable for integration, but is less straightforward to implement more light colours per optical waveguide.

INTEGRATED MODULATORS

Integrated modulators can be used for two functions in phased-array antennas. In the first place, they may be used to convert the RF signal into an optical signal. This may also be achieved by a direct modulation of the light source. In the second place they may be used to perform the beam forming.
Two types of high-frequency modulators are available: the electro-absorption modulator and modulators based on the electro-optic effect. A big disadvantage of the current modulators is the high drive levels required.
As an example of a modern modulator, we here show an InP OEIC that integrates both types of modulator at the same time and that was processed in our group [6].
In the OEIC shown in Figure 1, the 32 horizontal structures are the phase and amplitude modulators that use changes of the refractive index and in the absorption due to the electro-optic effect. The doping profile of the chip is chosen in such a way that the waveguide layer gets depleted when a

reverse bias is applied to the waveguide. At high voltages, the modulator acts as an electro-absorption modulator, due to the electrical field induced shift of the band edge. In the left side of Fig. 2 it can be seen that a phase shift of 180 degrees can be set with a voltage in the range of 0 to -5 V. The right side of Fig. 2 shows the attenuation as a function of the voltage. It is seen that an attenuation of over 15 dB can be achieved with an applied voltage of -20 V. Further, the OEIC shown illustrates the use of splitters and combiners, based on MMI couplers.

A predefined value for amplitude and phase can be reached as follows. First the attenuation in both the interfering arms has to be set by applying the same voltage to the phase/attenuation sections in both arms. Next the phase can be adjusted by changing the voltage on both arms relative to each other with a small amount. The OEIC hence can potentially perform the complete beamforming for 16 antenna elements.

INTEGRATED SOURCES

The integrated optical sources that are available, the semiconductor LED and laser, show large linewidths, at least in the order of MHz for a diode laser and far higher values for LEDs. This is generally not compatible with phased-array system specifications.

For the optical generation of microwave signals with higher spectral purity than the laser, an Optical Phase Locked Loop (OPPL) is of interest because of its potential to significantly reduce the relative phase noise of a pair of lasers [7].

In Fig. 3 a schematic diagram of an OPLL is shown. In an OPLL the microwave signal is generated by mixing the output of two lasers onto a photodiode. This microwave signal is amplified and its phase is compared to a reference signal oscillator. The resulting phase error signal is used to tune the frequency of the slave laser, which is forced to track the master laser with a frequency offset equal to the reference signal.

An OPLL system is realized consisting of a New Focus 1.55 μm external cavity diode laser (linewidth <300 kHz) operating as master laser, and a tunable 1.55 μm three section DBR laser diode (linewidth <5 MHz) acting as the slave laser in the loop. OPLLs based on semiconductor laser diodes offer the advantage of small, rugged devices but special attention is needed to the laser linewidth, tuning characteristics of the laser and total loop delay. In order to minimize the loop delay, micro-optic components are used for mixing of the optical signals and a special GaAs MMIC containing the electrical components like monolithic integrated photodiode, microwave mixer, amplifier and loop filter is designed and realised. An integrated MMIC, hence a small device, is necessary in this architecture in order to obtain the required very small loop delay. At the moment the complete OPLL system is being tested.

The optical signal used in the phased-array system has to be transferred back into an electrical signal by means of a photodetector. Mainstream detectors are PIN and MSM detectors. The main issues are responsivity and bandwidth, and a large variety of devices and processes has been reported. Frequencies as high as 40 GHz are not exceptional, and travelling-wave photodetectors have shown cut-off frequencies well above 100 GHz.

CONCLUSION

In this paper the development of photonic integrated circuits applicable to phased-array antennas is sketched. It is believed that this integration will lead to a wide-spread use in phased-array antennas, starting with the beamforming network.

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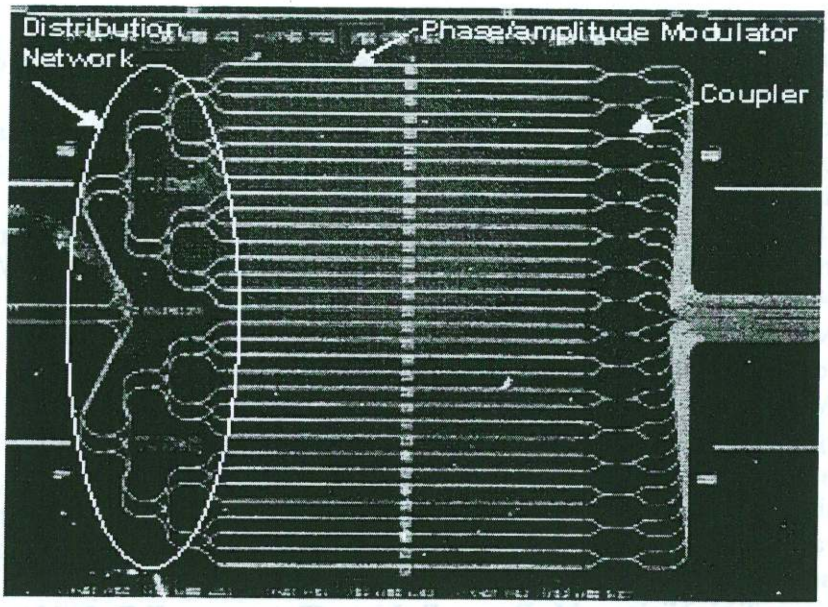

Figure 1 : Photograph of integrated beamforming chip, dimensions 8.5*8 mm^2

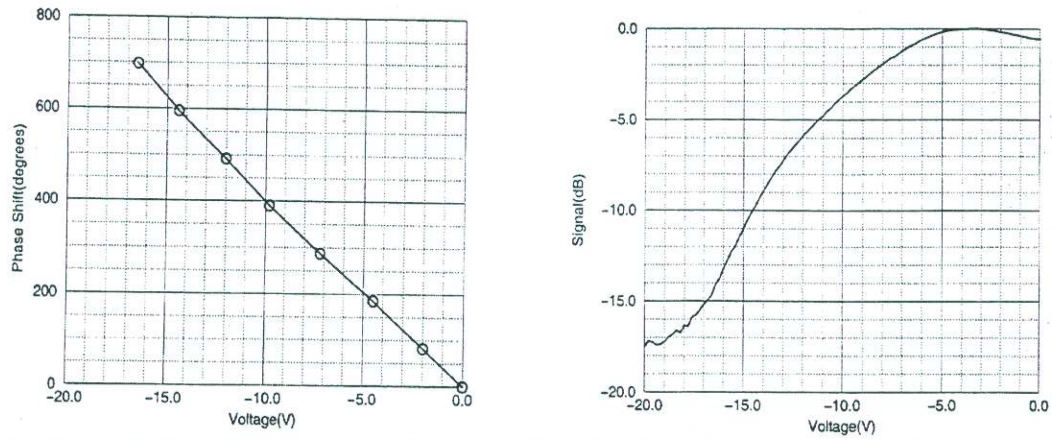

Figure 2 : Phase shift and attenuation as function of applied voltage

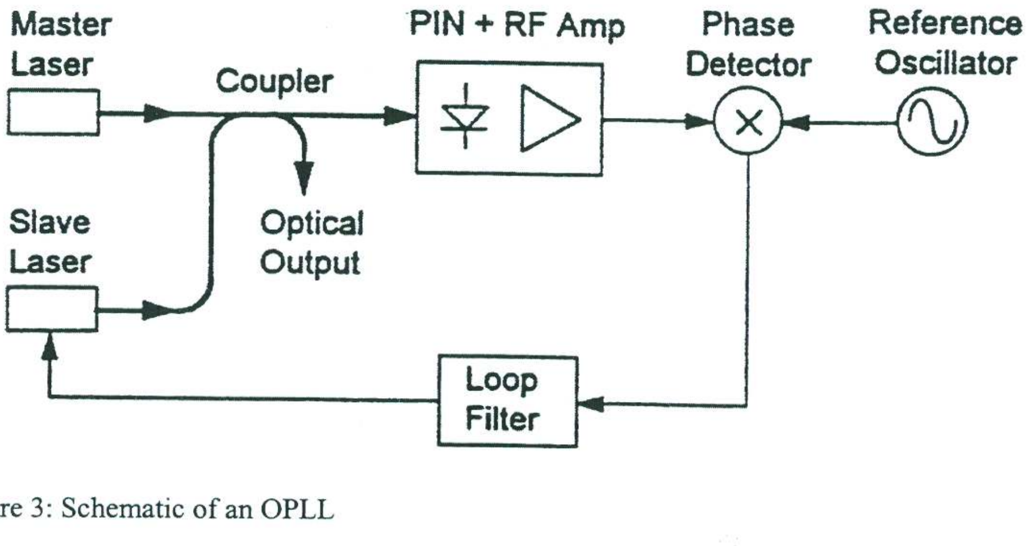

Figure 3: Schematic of an OPLL