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Optical Beamforming Networks for Radars & Electronic Warfare Applications

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Introduction

Future microwave systems will be generally based on active electronic antennas. This evolution is determined by requirements of improved performances of these equipments in terms of reliability, jamming resistance, flexibility for the beamforming in the transmit and in the receive mode.

Such antennas will be use in a large number of applications such as radar, communication and electronic warfare. In order to satisfy this multifunctional aspects, it will be necessary to distribute these antennas on ground based areas as well as the aircraft surface. Multistatic systems will impose multiple remoting of antennas with respect to their processing units.

In all cases, it appears a need for low loss link able to remote the control of the antennas as well as distribution and processing of very wideband microwave signals (typ. 1-20 GHz).

Maturity and performances (in terms of spectral purity or phase noise, dynamic range linearity) of optoelectronic components permit to envisage the optical transmission and the optical processing of these signals.

Today, the optical transmission of microwave signals offers in conjunction with their low loss propagation over very wide frequency bandwidth, a high immunity to electromagnetic perturbations, which opens new avenues for the insertion of new concepts and photonic architectures in microwave systems.

Photonics and microwave technologies offers new opportunities for controlling many thousand array elements together with handling the wide bandwidth of shared aperture antennas. Photonics technologies will provide an interconnect solution for future airborne phased array radar antennas, which have conformality, bandwidth, EMI immunity, size,and weight requirements increasingly difficult, if not impossible, to meet using conventionnal electrical interconnect methods.

The first set of applications envisaged for the microwave optical links is the replacement of coaxial cables and especially of wideband coaxial cables. It requires low insertion loss and low noise figure.
The second set is associated to a remote control of antennas or processing equipment
It requires simultaneously for a single microwave channel both low insertion loss and high dynamic range and for multichannel phase pairing

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Remoting of narrow band signals for radar antenna remoting and wideband antenna remoting and phase pairing for interferometry (ESM function).

The third set of applications is the delay function. In the microwave domain this function is of paramount importance due to the actual lack of digital function able to store a wide bandwidth signals. This represents the memory of microwave signals

Distribution of microwave signals

In future generation phased array radars, signal distributions will have to fulfil strict performance criteria. These include high isolation from both electromagnetic interference and crosstalk between module or subarray feeds with increased instantaneous bandwidths; dramatic reduction in size and weight regarding present fielded radars; and performance compatible with growing requirements such as low phase noise and high dynamic range.

The 1 to N distribution of microwave is extensively used in the telecomuunication or digital signals networking for send informations from one central board to N secondary ones.
In conventional telecommunications networks as well as in long distance networks it is required to detect and re-amplify the signals in order to avoid any distortions (low BER (bit error rate)) . The first application of optical amplifiers (see chapter II) is linked to the distribution of high speed digital signals.
In phased array antennas, an equivalent of this situation is found. In order to distribute local oscillators to active antennas arrays, we require to distribute high spectral purity signals. In complex environment (constraints of volume), optoelectronic technologies could bring a strong advantage to phased array antennas.

Optical architecture for phased array antennas

The beamforming, over a wide frequency instantaneous bandwidth of a phased array antenna requires a control of delay or at least a combination of phase and delay. The large amount of delay ($\approx$ 10 ns in order to compensate for the size of large antenna and $\approx$ 6 to 8 bits of phase between 0 et 2π to obtain the low level of secondary lobes secondaires) do not allow the use of control architectures based on microwave technologies (dispersion and insertion losses of microwave waveguides, interconnection complexity).

1 Review of Optical beamforming networks architectures

1.1 Optical Architectures : state of the art

As pointed out True Time Delay (TTD) beamforming is required when wide band operation is combined with significant beam steering offset. In this case there is a need of low loss transmission links allowing the remote control of the antennas and the distribution of large bandwidth microwave signals. This need is fulfilled today by microwave optical links, owing to an increase in the modulation bandwidth and the dynamic range of optical emitters and detectors. Furthermore, optoelectronic architectures, because of their inherent parallel processing capabilities, bring attractive perspectives for radar signal control and processing.

According to these considerations, a large number of Optical Beamforming Networks (OBFN) have been proposed during the last decade. One can classify these architectures according to five generic approaches :

- switched delay lines
- laser/photodiode switching
- wavelength coded architecture: dispersive delays/Bragg grating delays
- 2D optical delay lines.
- coherent OBFN

For each approach we will detail in the following a typical demonstration that already includes a built array. This overview is completed with related published references.

1.1.1 Coherent beamforming network

This approach is based on the generation of the phase delays to be distributed onto the antenna, through the use of dual frequency optical carrier of the microwave signal.
This concept can be illustrated by the experiment performed by Tamburrini & al.

Two mutually coherent, frequency offset optical beams are obtained by injection locking a slave laser (SL) with the emission of a master laser (ML), which was frequency shifted by a Bragg cell operating at frequency f = 3.2 GHz. These thus beams interfere and give rise to a moving interference pattern. A regularly spaced array of multimode fibers is used to spatially sample the moving pattern and to transmit the optical signals to the antenna plane. The light intensity coupled into each fiber varies at the beam frequency f with a microwave phase depending linearly of the fiber position and of the angle between the interfering beams. Phased array beam steering is achieved by changing the angle between the beams, thereby changing the spatial period of the interference pattern. The far field pattern of a 7 element linear antenna was characterised.

This concept was revisited (see references) but all these different approaches are based on the optical control (integrated optics, free space,...) of the microwave signal by changing the relative phase of the optical components of a dual frequency beam. It provides generally simple structures but does not permit a large frequency bandwidth operation of the antenna since these architectures only perform phase scanning.

1.1.2 Switched delay lines

This approach is based on the optoelectronic switching of fiber delay lines. This switching provides a digital control on the path lengths experienced by an optical carrier microwave signal and thus permits a true time delay control of a phased array antenna. This concept can be illustrated by the experiment performed by Goutzoulis et al. The operating principle is shown in the following figure 2.

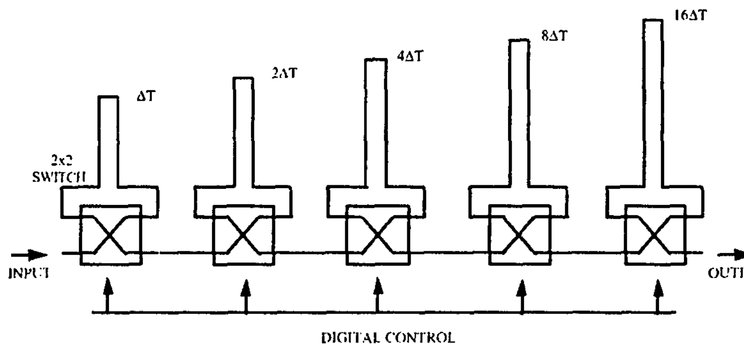

Figure 2: switched fiber delay lines

In the binary fiber optic delay line (BIFODEL) architecture, the optical carrier of the microwave signal is optically routed through N fiber segments whose lengths increase successively by a power of 2D. The required fiber segments are addressed using a set of N 2x2 optical switches. Since each switch allows the signal to either connect or bypass a fiber segment; a delay T may be inserted which can take any value, in increments of ΔT, up to a maximum value T_{max} given by :

$$T_{max} = (2^N - 1)T$$

For each reading element or subarray of a phased array antenna it is necessary to implement such a BIFODEL. It yields that this technique is very well adapted to a TTD control of a subarrayed antenna.

The performances of this concept can be extended, mainly for an antenna divided in subarrays, according to the use of optical wavelength multiplexing. This approach is the one proposed by Westinghouse in its proof of concept demonstration (Goutzoulis et al,).

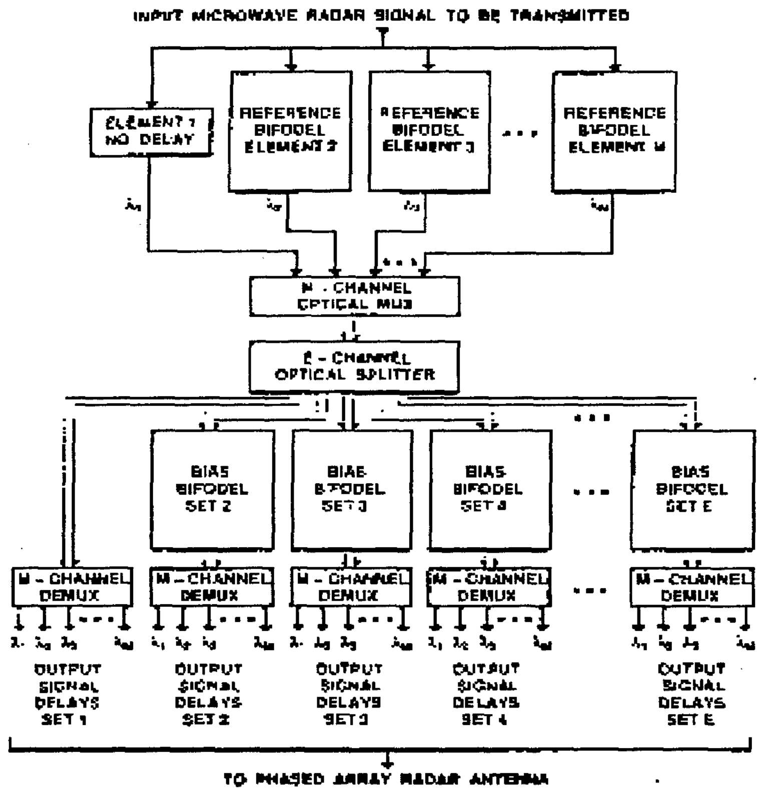

Figure3: BIFODEL architecture

The partioned phased array concept can be implemented using optical WDM in conjunction with all optical programmable delay lines. Furthermore it is reversible since the hardware can be used for both transmit and receive modes.

In the transmit mode *M-1* BIFODELs with outputs at wavelengths λ_2, ..., λ_M are driven in parallel radar signal. The *M-1* BIFODEL outputs, along with an undelayed output at wavelength, λ_1, are multiplexed via an *M*-channel multiplexer (MUX), the output of which is divided into *E* channels vie a 1:*E*-channel optical divider.

All but one of the divider outputs independently drive a bias BIFODEL, each of which is followed by an optical *M*-channel demultiplexer (DEMUX) output will also contain *M* wavelengths, λ_1, λ_2, ..., λ_M. The outputs of the nonbiased DEMUX contain the *M* progressively delayed signals required for the set 1.The outputs of each the remaining DEMUXs contain a similar set of signals but they are further delayed via the bias BIFODELs.

Similar wavelength outputs drive similar location elements in each set. All BIFODELs must have

$N = \log_2 R$ cascaded segments and different time resolution T_{imin}. The latter is determined by the location of the specific element, the antenna geometry, the radar characteristics, and so on. Similar comments apply to the bias BIFODELs, which have time resolutions $(j-1)T_{Mmin}$. In the receive mode, the same architecture is used, but in reverse. Here, the output of each element of the phased array drives an LD of a different wavelength. Elements with similar locations in different sets drive LDs of the same wavelength.

The experimental demonstration of this concept was performed at Westinghouse (Northrop-Gruman) for a 16 element linear antenna (16 elements for the transmit mode, 8 elements for the received mode). The far field pattern was characterised for both modes over the frequency range 600-1500 MHz for the distribution of the microwave signals. The antenna is divided in 4 subarrays. The microwave signal is first divided in parts, 3 of them can be electrically delayed (from 8 ps to 1500 ps with a 1.5 ps accuracy). The output of the non delayed line end of the 3 delayed lines are used to feed 4 directly modulated semiconductor lasers at different wavelengths.

1.1.3 Thales Approach

Inisde Thomson-CSF, this approach is under evaluation and development.
One of these is an architecture essentially 1D based on the delay switching (figure 4 - in this case, switching matrices base on cascade InP (IEMN - Lille) and WDM).

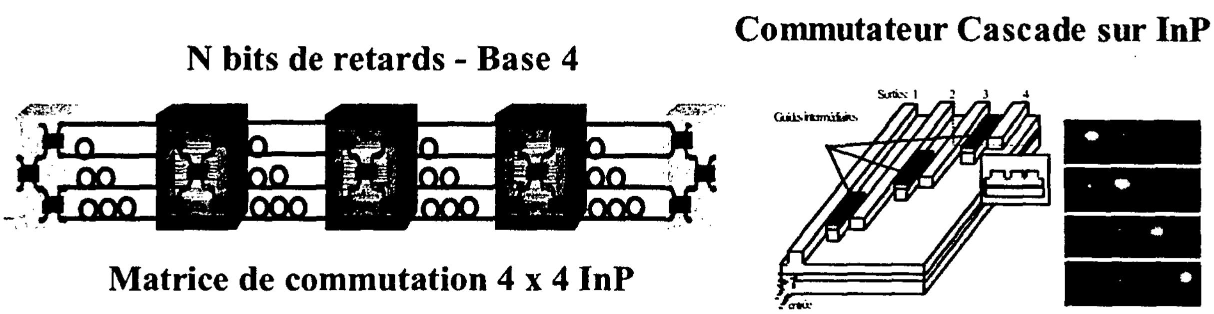

Figure 4: Base 4 switched delay lines

1.1.4 Laser / photodiode switching

In this approach (originally proposed and demonstrated by Hughes Aircraft), the delay path of the optical carrier of the microwave signal is defined, for each radiating element or subarray, by selectively turning on a laser and detector located respectively at the beginning and end of an analog optical link.

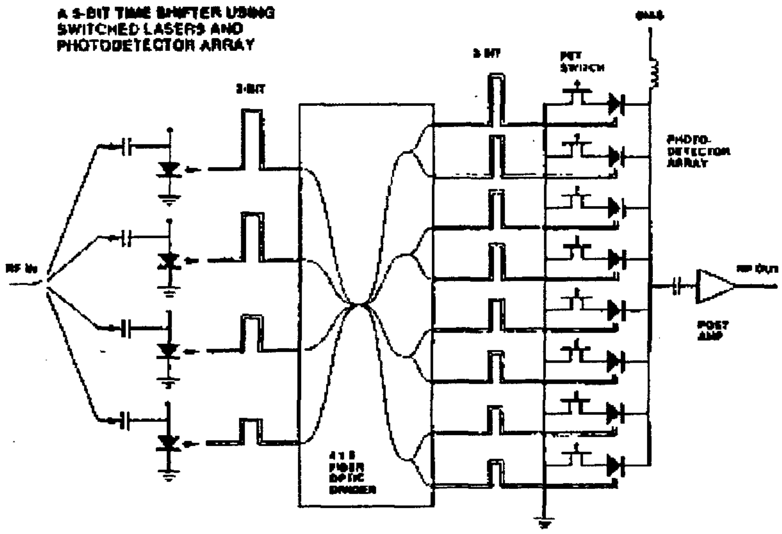

Figure 5: 5-bit time shifter

Combining laser and detector switching the network of the above figure (figure 5) provide 32 delay options (i.e 5 bits of resolution). This 5 bit time shift module is the building block of a wide band feed network. The programmable time shifters (8) provide the coarse delay steps ranging from 0.25 ns to 8 ns (5bits) for the 8x3 subarrays of a 96 element antenna. Electronic delay lines in the T/R modules provide fine differential delays ranging from 0.01ns to 0.5 ns (6 bit precision).

According to this concept both transmit and receive modes of a 2D conformal antenna were characterized over the frequency bandwidth 850 – 1400 MHz. This proof of concept is, at the moment the most achieved demonstration of optical remote control and beamforming of a large bandwidth antenna.

1.1.5 Dispersive delays / Bragg grating delays

1.1.5.1 Dispersive delays

In this approach, the time delays experienced by optically carried microwave signals are provided by the use of one or several tunable wavelength lasers in conjunction with a wavelength selective material. This material is either an optical fiber including permanent Bragg gratings (Lembo et al. from TRW, Smith et al. From GEC-Marconi) or an optical fiber used in its dispersive region (Frankel et al. from the Naval Research Lab.).

In the following we will detail the NRL approach, since it is already demonstrated with a radiating antenna.

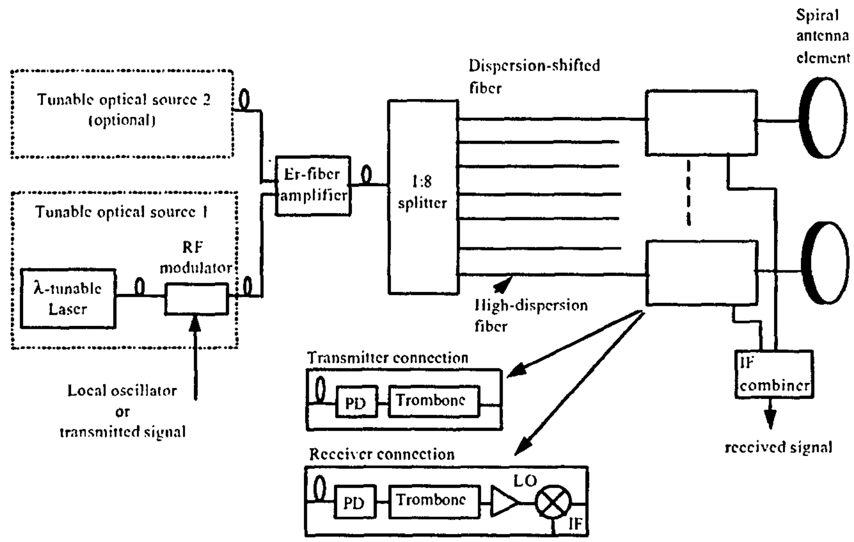

Figure 6: dispersive delays

The microwave signal driving the antenna elements is transmitted on a single wavelength-tunable optical carrier via a bank of dispersive fiber optic links. The TTD function is realized by tuning the carrier wavelength to vary the group velocity of the propagating signal. Each fiber link feeding an array element incorporates an overall amount of dispersion proportional to the element position. A set change in the carrier wavelength provides the necessary proportional time delay for all array elements with a single wavelength control input.

This approach seems to be very well adapted to linear antenna, with a number of elements in the range 10-100. It was experimentally demonstrated, for the transmit mode, with a very large bandwidth antenna (2 – 18 GHz) of 8 radiating elements. Receive mode operation is also possible with this concept when the optical beamformer is used to generate a properly phased local oscillator. In this case, a tunable laser is used in the module.

This fiber prism technique has since been shown to transmit multiple simultaneous beams and has been extended to a two-dimensional arrangement that operates over the full 6-18 Ghz band.

1.1.5.2 Bragg grating delays

Several laboratories have investigated the use of Bragg fibre gratings to provide true time delay beam steering in optically controlled phased array antennas. These studies have considered the performance of single channel discrete multi grating arrays (C.Edge & I Bennion) as shown in the following figure, chirped grating beamformers and full transmit /receive antenna systems.

Generation of TTD using multi element or chirped gratings is advantageous since all of the required delays for a single antenna element can be provided on one fibre rather than the more complex switched time delay modules described in the previous section. There are significant disadvantages however including the manufacturing reproducibility of fibre gratings, the requirement for highly wavelength stable tunable laser sources (only currently available in bench top form and with slow tuning speeds) and the ability to achieve suitable close-to-carrier phase noise performance within a system (BAES).

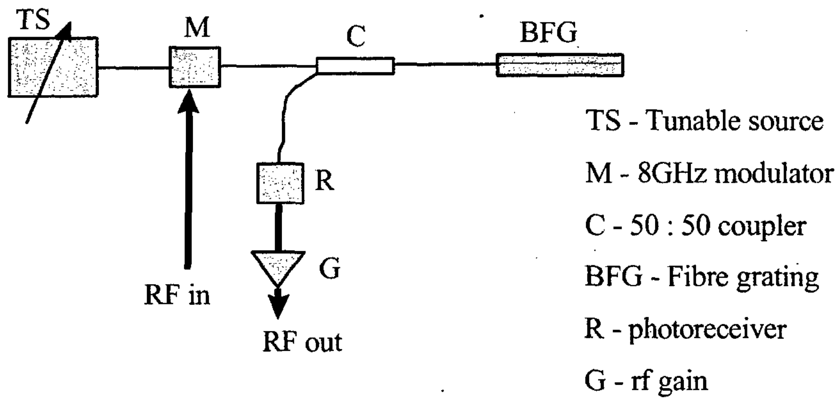

Figure 7: 8 element (3-bit) Bragg fibre grating test configuration

1.1.6 2D optical delay lines

A 2D optical delay lines has been implemented and demonstrated (cf Dolfi & Riza).
In this approach the time delays are provided by free space delay lines, switched using 2D spatial light modulators (SLM).

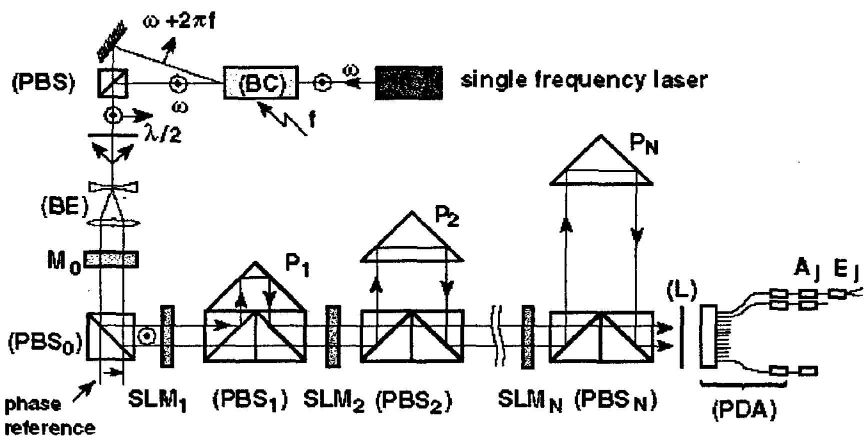

Figure 8: 2D optical delay lines

A dual frequency laser beam is the optical carrier of the microwave signal. This beam is expanded and travels through a set of SLMs whose number of pixels (pxp) is the number of radiating elements of the antenna. M_0 is a parallely aligned nematic liquid crystal (LC) SLM. It controls the phase of the microwave signal by changing the relative optical phase of the cross polarized components of the dual frequency beam.
At the output of M_0, the linearly polarized dual frequency beam intercepts a set of spatial light modulators SLM_i, polarizing beam splitters PBS_i and prisms P_i. They provide the parallel control of the time delays assigned to the antenna. The beam polarization can be rotated by 0° or 90° on each pixel. According to the polarization, PBS_i is transparent (and the light beam intercepts the next SLM_{i+1}) or reflective (and the microwave signal is delayed). The collimated beam travels through all the (PBS_i) and is focused by an array of microlenses (L) onto an array of pxp fiber pigtailed photodiodes (PDA).

For a given photodiode, the phase of the microwave beating signal is determined by the applied voltage on the corresponding pixel of M_0 and by the choice of the PBS_i on which the reflections occur. Since the positions of prisms P_i provide delay values according to a geometric progression (t, 2t, 4t..), the beating signal can be delayed from 0 to $(2^N-1)t$ with step t.

Experimental demonstration of an optically controlled phased array antenna, operating between 2.5 and 3.5 GHz. The 2D architecture is implemented with 6 SLMs of 4 x 4 pixels. It provides 32 delay values (5 bits), an analog control of the phase [0,2p] and permits the control of a 16 element phased array antenna. Furthermore, when far field patterns at different frequencies are superposed for a given scan direction , one can notice the absence of any beam squint.

1.2 Optical Beamforming Receive Mode – Thomson-CSF 2D Approach

We propose and experimentally demonstrate two optical architectures performing processing of the receive mode of a p×p element phased array antenna. They are based on free space propagation and switching of channelized optical carriers of microwave signals. The first architecture assumes a direct transposition of the received signals in the optical domain. The second one is based on the optical generation and distribution of a microwave local oscillator matched in frequency and direction. Preliminary experimental results at microwave frequencies of about 3 GHz are presented.
The review presents an original architecture dedicated to the processing of the receive mode, using a similar concept as the one demonstrated in for emission. In the Direct Architecture, the received microwave signals are optically carried and travel back through the same time delay network as the one used for the transmit mode. In the Matched Local Oscillator Architecture (MLOA), a channelized microwave local oscillator, time delayed and optically carried, is mixed, at the antenna level, to the received signals. It provides an heterodyne filtering, matched in frequency and direction, to the received signal. Such an approach was recently considered with quite different implementations. We propose here a third implementation, fully programmable and based on the optical generation of simultaneous complementary delays for both the transmit signal and the Local Oscillator (LO).

When now using this architecture in the receive mode, the microwave signal reflected by the target travels back to the antenna, and is detected by an array of p×p microwave receivers. The signals issued from each receiver are used to feed an array of modulated lasers (direct or external modulation). For a radar detection in the same direction as for emission, the received signals, optically carried, have to travel through the same time-delay network as the one used for the emission mode. It permits in-phase addition over a large frequency bandwidth of all the microwave signals received by the antenna. An array of p×p photodiodes then extracts the microwave information from the optical carriers for processing.

This detection mode leads to some important problems. Indeed, robustness to jamming requires opto-electronic elements able to handle high power microwave signals. In the same time, they must be able to detect very low level signals, corresponding to the target signatures in limit of range. The ratio jammer signal to lower signal requires linearity of opto-links in the range 100 – 120 dB. This corresponds to spurious free dynamic range (SFDR) in the range 70 – 80 $dB/MHz^{2/3}$. Such performances are still difficult to attain over large bandwidth with currently available opto-components. This first architecture, using direct transposition of the received microwave signals, is operating with a time-reversal approach. In the following, we then detail an approach using a Matched Local Oscillator that operates in a similar way as phase conjugation (Fig.9).

In order to overcome this dynamic range limitation, we have developed the MLOA, in which a channelized microwave local oscillator, optically carried, is used for mixing with the received microwave signals. The operating principle is shown on Fig.9. In a similar way as the one on Figure 8, two optical beams are excited by a microwave signal at f_e and f_{LO} respectively. In the emission mode, for a frequency f_e and a time-delay τ_k, the phase of the radiating element *k* is

$\varphi_k^e(t)=2\pi f_e(t-\tau_k)$. (1)

After a round-trip time 2T from the antenna to the target, receiver *k* detects a signal of phase :

$\varphi_k^r(t)=2\pi(f_e+f_D)(t-2T+\tau_k)$ (2)

where $f_D<<f_e$ is the Doppler frequency due to the target velocity. In the following, $f_r=f_e+f_D$ is the received frequency associated to f_e. As for the emitted signal, the microwave LO, with (principal) frequency f_{LO}, is channelized and optically carried through the time-delay network. The carriers are detected by a p×p photodiodes array. Each photodiode provides a microwave signal of frequency f_{LO}, time-delayed according to the law given by the delay network. Each of those channelized microwave signals is then mixed, at the T/R module level, with the corresponding component of the received signal. It results in a low-frequency microwave signal of phase :

$\varphi_k^s(t)=\varphi_k^{LO}(t)-\varphi_k^r(t)$ (3)

where φ_k^{LO} is the phase of the Local Oscillator. The delay law experienced by the LO is chosen to perform in-phase addition of all the low intermediate frequency signals coming out of the mixers. To achieve this condition, a remarkable property of an optical architecture based on liquid crystal SLMs can be used here. When two cross-polarized beams travel along the same channel, their polarizations stay cross-polarized, and they experience complementary paths. One of the two beams is delayed by τ_k, the other (cross-polarized) by $(\tau_M-\tau_k)$, where τ_M is the maximum time-delay. According to (1), if we choose the LO complementary to the emitted signal, the phase of the LO will be:

$\varphi_k^{LO}(t) = 2\pi f_{LO}(t-(\tau_M-\tau_k))$. (4)

According to (2), (3) and (4), the resulting mixed signals will have the phase

$\varphi_k^s(t)=2\pi(f_i(t+\tau_k)-f_{LO}\tau_M+2f_rT)$, (5)

where $f_i=f_{LO}-f_r$ is the intermediate frequency, and the term $2\pi(f_it-f_{LO}\tau_M+2f_rT)$ is common to all the channels. In the case of an homodyne detection, where we would have $f_{LO}=f_r$, the phase, at the output of each channel, reduces to $\varphi_k^s(t)=2\pi(f_{LO}\tau_M+2f_rT)$, and ensures that all the channels are added in phase. Note that for an emitted signal with a large frequency bandwidth, the condition $f_{LO}=f_e$ is satisfied for each component of the spectrum, by using a large frequency bandwidth local oscillator. By this way of complementary path, we can therefore generate a perfectly matched LO. In order to avoid any crosstalk between emission and reception, the wavelength of the LO and the emission optical carriers have to be different. At the output of the delay network, a dichroïc mirror switches the carriers on two different photodiodes. One will provide the signal to be emitted, the other one the microwave LO signal.

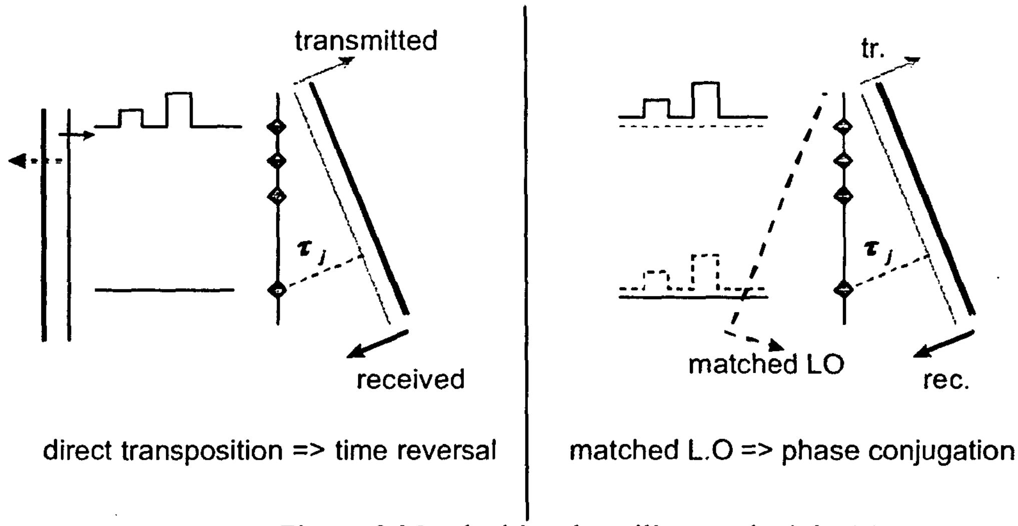

Figure 9 Matched local oscillator principle (a)

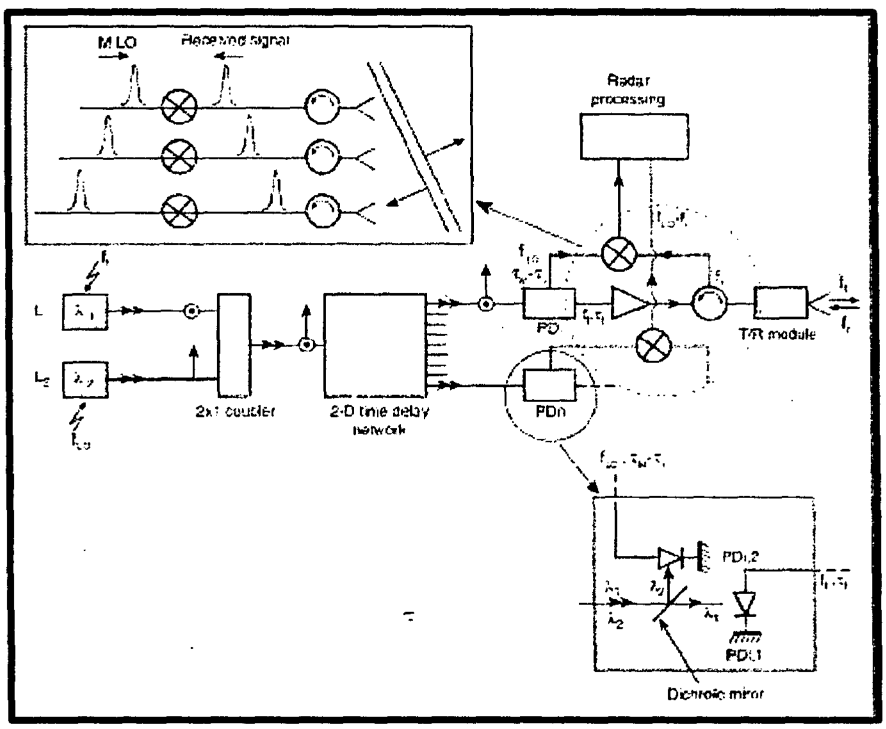

Figure 9 Matched local oscillator architecture (b)

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