OPTICAL FUNCTIONS FOR MICROWAVE SIGNAL PROCESSING IN RADAR, COMMUNICATIONS AND SURVEILLANCE SYSTEMS

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Abstract— **The optical-microwave technologies have appeared as promising for the next generations of radar, communications and surveillance systems. The new concepts and demonstrations show the improvements of optoelectronic links and the capability to perform processing functions, in the optical domain, like the local oscillator distribution for both ground/ship based and airborne radars, or the radar receive mode processing with optical architecture dedicated to radar beamforming and to down/frequency mixing.**

Index terms – photonics, fibre optics, laser, microwave oscillators, phased-array antennas.

I. INTRODUCTION

The fibre-based communications are now well established in transmission systems. Then photonics solutions have become major technologies for advanced communications, radar and surveillance systems. The maturity and the performances, in terms of spectral purity and linearity, of optoelectronic components, are such that today they enable optical transmission and processing of analogue broad-bandwidth microwave signals. Moreover the inherent parallel nature of light and the low sensitivity to electromagnetic perturbations of the fibre-based transmissions allow the introduction of new concepts and their validation into ship or ground-based radars, as well as into space or airborne systems.

The analysis of needs of this large domain leads to the necessity of low noise (intensity and phase) optoelectronic links for antenna control, signal distribution and processing of broad-bandwidth analogue signals.

For a long time, the electrical-to-optical converters struggled to afford the linearities, which were fully compatible with the required dynamic in the radar receive mode range. Therefore, for the new generations of radar systems, it was necessary to propose solutions to increase the dynamic range and the linearity of the optical links.

The spreading out of the optoelectronic technologies inside radar systems have also got through the realization in optics of a large number of elementary radar functions like optical beam-forming, adaptive filtering or radar waveform generation.

II. OPTICAL DISTIBUTION OF RF SIGNALS

While microwave signal distributions inside the radar systems have become more complex, especially for the large antennas, requiring phased array and multi-beam allocations, photonics solutions have proven their ability and reliability to address the challenge of high-density integration. For instance, future active antennas will use Transmit/Receive modules located behind antenna elements. These kinds of antenna will operate from L to X band. In this architecture both emitted/received signals and Local Oscillator (LO) frequency can be distributed through an optical network to avoid complex microwave circuit distribution

In the elementary step, Thales has validated technical solutions enabling high-quality broadband analogue signals transmission over fibre under extreme environmental

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conditions. An example of airborne-qualified fibre connectors is displayed on figure 1.

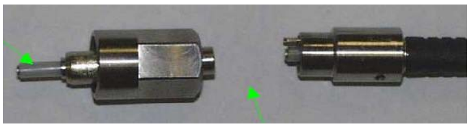

Figure 1. Airborne-qualified fibre connector, based on a dismountable noise for safer and easier maintenance.

Telecommunication-optics based solutions, like structured enhanced modules set with representative photonic components (laser, photoreceiver, electro-optic modulator, fibre coupler,…), have been ruggedised for harsh conditions and bench-tested over severe aircraft gauges (temperature form -40°C to +85°C ; random vibrations: 0.8 g^2/Hz from 10 Hz to 100 Hz then 0.4 g^2/Hz from 100 Hz to 2 kHz ; 10-g accelerations and 20-g shocks).

Radar system simplifications also follow from the insertion of wavelength multiplexing. Hence RF, LO and digital signals are simultaneously transmitted through a single fibre [1]. Figure 2 shows how the combination of optical multiplexing and optical rotary joint achieves bidirectional transmission of high volumes of data trough a single and compact device.

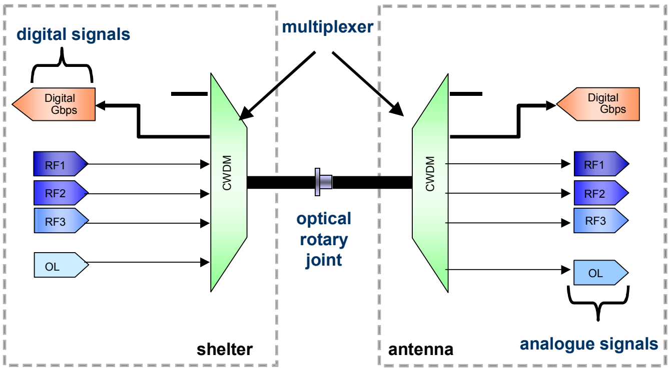

Figure 2. RF and LO signals are transmitted from through both the multiplexers and the rotary joint. The digital signal is transmitted in the opposite direction.

III. LOW INTENSITY NOISE SEMICONDUCTOR LASERS

After validation of optical architectures to overcome the limitations of standard RF manifolds, the current studies aim to match the required specifications for high-dynamic range RF links over broad bandwidths. Our investigations have focused on low noise laser sources [2].

The commonly used semiconductor lasers, such as distributed feed-back lasers, produce intensity noise that is usually the dominant contribution to dynamic-range limitations in optical links. Since excess intensity noise arises from inherent relaxation oscillations (R.O) behavior of such lasers, an alternative approach consists in suppressing R.O through improved laser dynamics. The latter dynamics is obtained when the photon lifetime exceeds the carrier lifetime. For this purpose, the active gain medium (a half Vertical-Cavity Surface-Emitting Laser) is placed in an extended optical cavity, closed by an output mirror and pumped by an external laser diode. The setup built in Thales R&T is depicted in figure 3 [3].

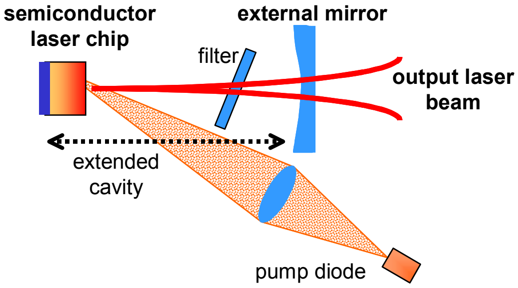

Figure 3. Experimental setup for the low-noise laser source. The extended cavity (formed around a half VCSEL chip) is 45-mm long. The output power exceeds 50 mW, at 1000 nm.

A typical result of the relative intensity noise (RIN) measurement of the laser source is displayed in figure 4. The resulting optical noise is white and coincides with the shot noise level. It proves that laser noise contribution can be significantly reduced below noticeable levels, namely -172 dB/Hz for 50-mA detected photocurrent.

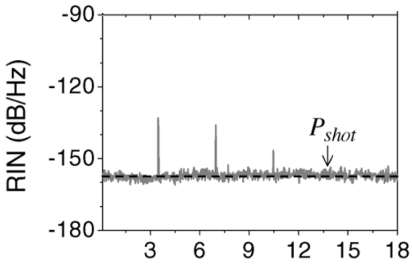

Figure 4. Intensity noise spectrum measured from 100 MHz to 18 GHz. The laser noise (RIN) level is given by the expected shot noise relative level lying at –155 dB/Hz for the detected photocurrent value. The dashed black line coincides with the shot noise relative level (P_{shot}). Excess intensity noise is observed at 3.4, 6.8, and 10.2 GHz, harmonics of the cavity free-spectral range.

The intensity-noise properties of this laser now offer new opportunities for stringent radar applications requiring ultra-low noise optoelectronic systems over broad bandwidths.

IV. OPTO-ELECTRONIC OSCILLATORS

In the case of distributed architectures as in phased array or digital beam-forming, where a great number of receivers are involved, the possibility to distribute the source signals in fibre optic may be quite useful. Moreover the possibility of modulated signals (like chirping) directly at very high frequencies open the way to new strategic architectures in which the concept of the superheterodyne receiver is overcome.

Opto-Electronic Oscillators (OEOs) appear as a very promising solution to meet these future requirements [4,5]. In addition such oscillators provide the inherent capability of a low-loss fibre-based distribution. Hence they allow optical clock distribution for synchronisation of radar digital-receivers, or they can be considered as a radar-signal generator with its associated optical distribution manifold.

Microwave oscillators are currently obtained mainly through a frequency multiplication from a highly stable quartz oscillator within the 100 MHz range. The spectral purity of these microwave oscillators is directly correlated to the multiplication factor, leading to noise floor around –130 dBc/Hz at 10 GHz, limiting clutter rejection performances. Improvements of the phase noise of oscillator loops are obtained if the phase noise of the loop elements is reduced and/or if the resonator Q factor is increased.

One of the solutions to improve the resonator performances is based on the conversion of the microwave signal into an optical signal and on the use of the low-loss properties (or high Q) of some optical devices such as optical delay lines or optical resonators [6]. This leads to the basic principle of such an OEO as described on the figure 5.

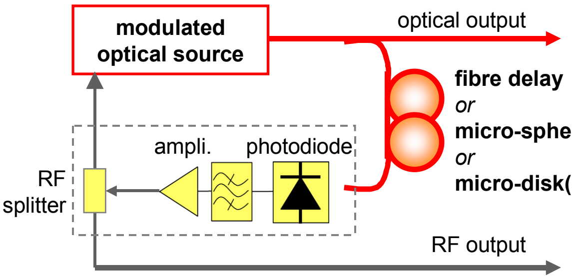

Figure 5. Principle of optoelectronic microwave oscillators, including a frequency-modulated optical source and a delay line (or an optical resonator).

The intensity modulated optical carrier propagates along an optical loop, made of either a fibre-based delay-line or an optical resonator (microsphere or microdisks [7]). The modulated optical signal is then detected, processed (e.g. filtered and amplified) in the electrical domain and fed back to the modulated laser source. Once the overall loop gain experienced by the optically carried microwave signal is larger than one, then microwave oscillation takes place. Basically, the ratio between the loop length (resp. the storage time in the loop) and the microwave wavelength (resp. the period of the microwave signal) sizes the spectral purity of such an oscillator.

Thales approaches for OEOs are either the use of mode-locked lasers [8] or dual-frequency optical source as the modulated laser source of microwave signals to be generated or duplicated.

At the component level, the OEO takes advantage of the use of dual-frequency beams in order to benefit from an improved optical efficiency (thanks to inherent 100% modulation depths), power level and spectral purity of such beams, as well as a reduction of the influence of chromatic dispersion (frequency bandwidth limitation due to signal fading and conversion of optical phase noise into RF intensity noise) in the required long delay lines, opening the route to the implementation of very high Q oscillators, potentially tuneable (up to 40 GHz in less than 10 µs). Through its optical output, the microwave frequency can be directly distributed to a linked optical manifold.

V. DUAL-FREQUENCY LASER SOURCES

As mentioned above, the dual-frequency laser (DFL) can be one of the key components to reach high-quality microwave frequencies [9]. This source relies on the optical heterodyne generation to provide optically carried RF signals tunable between 0.5 to (potentially) 127 GHz [10,11].

Thales demonstrated the operations of diode-pumped solid-state DFLs in phase-locked loops [8]. One setup, integrated in Thales R&T, is depicted on figure 6.

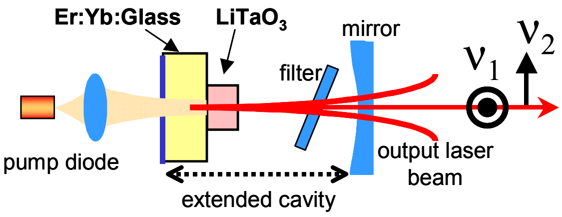

Figure 6. Experimental setup for the dual-frequency laser.

A $LiTaO_3$ birefringent electro-optical crystal is inserted within a classical diode pumped Erbium-Ytterbium-codoped glass micro-laser. The lasers outputs two power-balanced orthogonally-polarized optical beams at frequencies ν_1 and ν_2, which difference is related to the cavity length and the amount of birefringence. An etalon ensures a stable dual-frequency operation. The resulting electrical beat-note can be detected on high-speed photodetector, generating the heterodyne frequency difference $(\nu_1 - \nu_2)$ in the electrical domain. This scheme permits to use a single compact laser cavity to generate a beam which is 100 % intensity modulated, at a modulation frequency continuously tunable in the GHz range (20-GHz wide coarse tuning by changing the temperature, GHz fine tuning by changing the voltage applied to the electro-optical crystal). This DFL operates at optical wavelengths (1.5-µm window) which meet the availability and ease-of-use of widespread telecommunication optics (fibres, multiplexers,…).

Given its good efficiency (fiber-coupled output power above 10 mW, 100 % modulation depth), the DFL delivers high RF powers (0 to 10 dBm) through fibre, with a remarkably low phase-noise. Indeed, when phase-locked to a high-quality microwave oscillator, the beat-note phase-noise is measured to be as low as –130 dBc/Hz at 10 kHz offset. Furthermore, the laser intensity-noise reduction-loop could be upgraded in order to reach the still lower phase-noise value requested for radar LO applications (–130 dB/Hz to –150 dBc/Hz at 10 kHz offset), thanks to a better choice of individual component of the loop electronics. The ultimate phase-noise performances are limited by thermal and shot noises at photodetection. When inserted in an OEO-like setup, this laser has also proven to provide widely tunable, low-noise microwave signal without external reference, and without any need for an expensive and bulky high finesse RF filter like in classical OEOs [9].

Therefore Thales has now firmly established in a laboratory context that DFLs and OEOs offer wide possibilities for the generation and transmission of high-quality RF and microwaves signal over bandwidths exceeding 40 GHz, in rather simple optoelectronic setups.

VI. Insertion of RF Photonic Technologies into Phased Array Antennas

The previous considerations showed how Thales aims to meet with the main requirements associated with phased array applications: namely the need for high spectral purity LO generation and distribution and the need for high dynamic range RF links (including broadband links). Therefore photonic manifolds now afford many solutions to overcome classical electrical beam-former limitations.

It has been well established that optics offers unique capabilities for true-time delay (TTD) for Beam-Forming Networks (BFNs). While most of the experimented solutions rely on commuted discrete delay-lines, the architecture proposed by Thales [12,13] allows for continuous slowing of light signals. It is based on widely-developed sources and wavelength multiplexing which are nowadays completely mature and largely compliant regarding the dynamic needs of a 1D radar system, notably thanks to the optical summation capability. Indeed, this dispersive Optical BFN forms several simultaneous beams in one dimension. As depicted on figure 7, a comb of laser sources is associated with a set of dispersive fibres. The RF signals carried on the comb of wavelength-selected sources are coherently summed at the photodetection stage. This kind of summation, coherent in RF, but incoherent regarding photonic carriers, allows high dynamic ranges which are required for the receive mode. As time delay laws drive the pointing, no squint appears even through wide band operation.

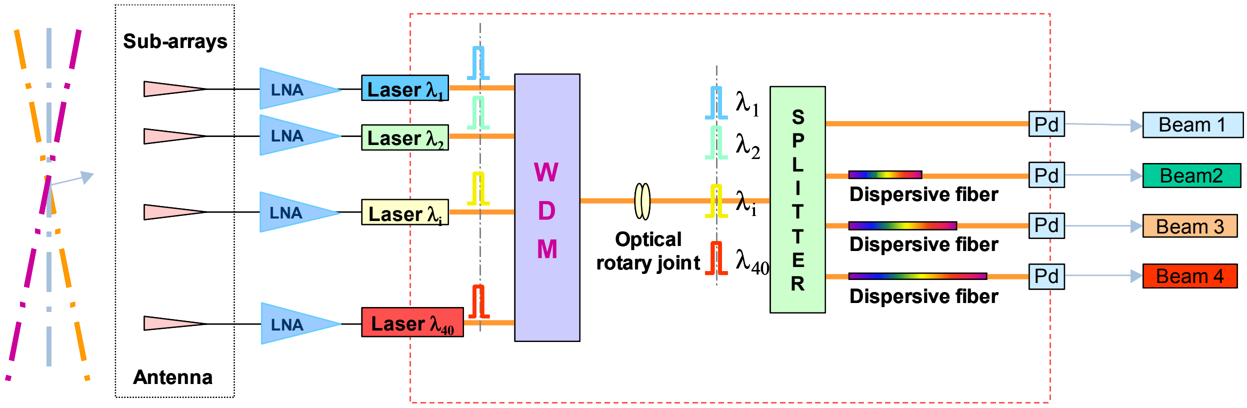

Figure 7. Dispersive Optical Beam Forming Network principle: RF signals from radiating elements are transferred on multiplexed optical carriers and addressed to a set of dispersive fibre lengths. Each length corresponds to a linear time delay law.

This kind of antenna will permit in future radar systems to obtain high performances in terms of reliability, jamming robustness, frequency-independence beam-steering of simultaneous multiple beams, while spanning multiple radar bands.

A last step in RF-photonics insertions concerns the optical processing of microwave signals for system functions enabling goniometry, interferometry, spectrum analysis [14], adaptive filtering, radar waveform generation [15], or microwave photonic synthesizer [16]. Indeed, since the trend in the radar evolution is to design systems operating on a broad bandwidth with complex waveforms, it becomes possible to design a photonic architecture with a waveform generator – including OEO, TTD, phase control or amplitude control – by changing not only the pulse rate but also the sort of modulation, frequency against amplitude for instance.

VII. Conclusion

This paper pointed out several examples of recent breakthroughs in the RF-photonics domain. On one hand, technologies originate from the telecommunication optics have led to mature and reliable solutions compliant with microwave transmission via fibre optics to advantage radars for remoting the radiating elements and the control of their relative phase. On the other hand, several innovative architectures directly benefit from the applicability improvement of these devices to allow LO distribution for both ground/ship-based and airborne radars, radar receive/transmit mode processing (with optical beam-forming) and down/frequency mixing.

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