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Optical Interference Suppression using MicroPhotonic RF Filter Structure

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Abstract--**The impact of laser coherence noise on conventional photonic RF filters is investigated in this paper. In addition, a new MicroPhotonic adaptive RF filter structure is proposed, which can simultaneously suppress the phased-induced intensity noise caused by optical interference. Results show that the coherence length of the laser light significantly degrades the RF frequency response of a photonic transversal RF filter, whereas the MicroPhotonic RF filter has the capability of generating arbitrary transfer function with no phase-induced intensity noise**.

Keywords: laser coherence, phase-induced intensity noise, photonic signal processor.

I. INTRODUCTION

The ability of photons to carry high information capacity, preserve their energy for a longer time than electrons, and pass near one another without generating crosstalk, has driven the use of fibres for adaptive wideband RF signal processing [1-3]. Photonic signal processors based on fibre optical cavities have been widely used for the realization of transversal RF filters through true-time RF delay generation [4-7]. However, these filter structures have two fundamental problems, namely:

- They generate substantial phase-induced intensity noise, caused by the long coherence length of laser sources.
- Their transfer characteristics cannot be arbitrarily reconfigured

Optical interference is a common problem encountered in photonic signal processing systems utilizing long coherence length lasers. In such systems, delayed RF-modulated optical signals, which may be originated by multiple reflections, connectors, or splices in the optical systems, can be converted to intensity noise that falls within the RF band, hence it cannot be filtered out.

The analysis of phase-induced intensity noise (PIIN) has previously been studied in details [8-12]. Tur *et al.* have theoretically and experimentally investigated the phased-induced intensity noise power spectrum of a fibre recirculating loop [8]. They showed that this noise significantly degrades the performance of a photonic signal processor and limits its high-frequency operation range. Moslehi has obtained a universal expression for the phase-induced intensity noise of a general optical RF signal processor [11], [12]. Although both analyses have accurately evaluated the interference, they have both ignored the interaction between the interference caused by the optical carrier and the modulating RF signal itself.

In this paper, we investigate the noise performances of a conventional 4-tap photonic RF filter, including the interference introduced by optical carrier and the RF modulation signal, and propose a new MicroPhotonic adaptive RF interference mitigation filter structure, which can simultaneously suppress the optical interference and synthesise arbitrary frequency responses. The proposed MicroPhotonic structure integrates a VCSEL array, a 2D ultra-wideband photoreceiver array and a multi-cavity optical substrate, and can achieve arbitrary, high-resolution RF filter transfer characteristics, with no phase-induced intensity noise. Results show that the coherence length of the laser light significantly degrades the RF frequency response of a photonic transversal RF filter, whereas the MicroPhotonic RF filter has the capability of generating arbitrary transfer function with no phase-induced intensity noise

II. CONVENTIONAL PHOTONIC RF FILTER

The architecture of the conventional photonic RF filter is shown in Figure 1. The laser output is intensity modulated by a transverse electro-optic amplitude modulator, amplified by an Erbium-Doped Fibre amplifier (EDFA) and fed into a $1{:}N$ optical power splitter. The split signals are delayed and then recombined with an $N{:}1$ optical combiner and the combined signal is detected by a photodetector. To investigate the impact of the laser coherence length on the RF response of the transversal filter, we assume a DFB laser source of a typical Lorenzian-shape spectrum modulated by a RF sinusoid. The electric field of the input RF-modulated optical signal is given by:

$$E_{in}(t) = [1 + M\cos\omega_{RF}t]e^{j\omega_0 t}\varepsilon(t) \qquad (1)$$

where M is the modulation index, and $\varepsilon(t)$ is the slowly varying envelop of the RF-modulated optical field, which is given by:

$$\varepsilon(t) = \int_{-\infty}^{\infty} \tilde{\varepsilon}(\omega) e^{j\omega t} d\omega \qquad (2)$$

Using Wiener-Khintchine theorem, the autocorrelation function of optical field can be defined as:

$$\Gamma(\tau) = \Gamma^*(-\tau) = \langle \varepsilon(t)\varepsilon^*(t-\tau) \rangle \qquad (3)$$

where <> represent an ensemble, or time-averaging process. Without loss of generality, we assume that $\varepsilon(t)$ is normalized such that $\Gamma(0) = 1$. $\Gamma(\tau)$ can be expressed in terms of the bandwidth $\pm\delta\omega$, the coherence length of the laser source l_{coh}, is given by:

$$l_{coh} \sim 2\pi c / \delta\omega \qquad (4)$$

For the conventional photonic RF notch filter shown in Figure 1, the output field $E_{out}(t)$ can be expressed as:

$$E_{out}(t) = \sum_{n=0}^{M} k_n \varepsilon(t_n^{'}) \cdot \left[e^{j\omega_0 t_n^{'}} + \frac{M}{2} e^{j(\omega_0+\omega_{RF})t_n^{'}} + \frac{M}{2} e^{j(\omega_0-\omega_{RF})t_n^{'}} \right] \qquad (5)$$

This shows that the output field $E_{out}(t)$ impinging on the photodetector has three spectral components at ω_0, and $\omega_0 \pm \omega_{RF}$ The photodetector current is given by:

$$I_{RF}(t) = A_{RF} \langle \varepsilon(t)\varepsilon(t-\tau)^* \rangle \qquad (6)$$

When the detection response time τ_d is sufficiently short, $1/\tau_d \ll \tau_0$, the detected current has three frequency components, namely: dc; ω_{RF} and $2\omega_{RF}$, which are referred to as the dc, RF and second-harmonic currents, respectively. The dc and second-harmonic currents are usually filtered out, and will not be discussed here. The RF response can be expressed in terms of its amplitude A_{RF} and phase ϕ_{RF} functions,

$$I_{RF}(t) = A_{RF} e^{j(\omega_{RF} t + \phi_{RF})} \qquad (7)$$

For an optical source of Lorentzian line shape spectrum, the autocorrelation function of optical field is given by:

$$\Gamma(\tau) = e^{-|\delta\omega\tau|} \qquad (8)$$

Substituting Equation 8 into Equation 6 yields,

$$A_{RF} = \left(\sum_{n=0}^{N} \sum_{m=0}^{N} k_n k_m e^{-|\delta\omega(m-n)T|} \cos[(m-n)\omega_0 T][\cos(m\omega_{RF}) + \cos(n\omega_{RF} T)] \right)^2$$
$$+ \left(\sum_{n=0}^{N} \sum_{m=0}^{N} k_n k_m e^{-|\delta\omega(m-n)T|} \cos[(m-n)\omega_0 T][\sin(m\omega_{RF}) + \sin(n\omega_{RF} T)] \right)^2 \qquad (9)$$

where N is the number of the ports of the splitter, T is the unit delay time for each optical path, k_i is the coupling ratio for each branch of the optical splitter and $\sum_{i=1}^{N} k_i^2 = 1$, if the splitter is lossless.

III. MICROPHOTONIC RF FILTER

MicroPhotonic architectures utilizing true-time-delay methods can perform broadband RF signal processing that cannot be achieved by the conventional photonic RF filter structure described in Figure 1.

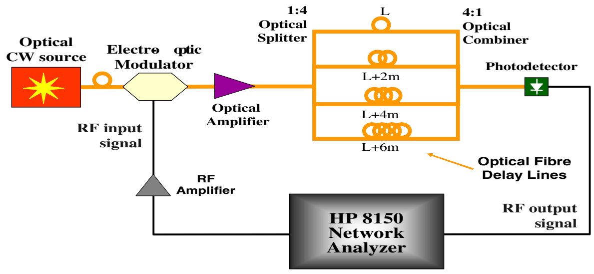

Figure 1. The configuration of conventional photonic RF filter

Figure 2 illustrates the principle of MicroPhotonic RF signal processing. An electrical-to-optical conversion array converts the input RF signal into many RF-modulated collimated optical beams, which are delayed directly in the optical domain via the optical delay generator that generates a large number of delayed optical beams. The delayed optical beams are photodetected and appropriately post-amplified by a photoreceiver array to produce a delayed RF signal with appropriate amplitude. By combining the delayed RF signals, an FIR transversal filter characteristic is synthesized, which depends on the amplitudes and the delay times of the combined RF signals.

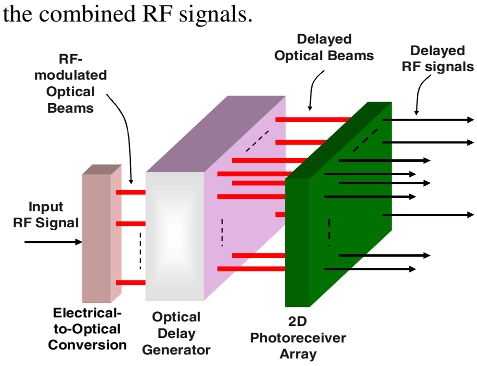

Figure 2. Principle of MicroPhotonic RF signal processing

The architecture of the MicroPhotonic RF filter is shown in Figure 3. The low-noise amplifier (LNA) pre-amplifies the input RF signal to compensate for subsequent splitting loss and also to boost the modulation efficiency of the VECSEL array (where the first E stands for "external"). The RF splitter equally splits the input RF signal into N RF signals, which modulate the N elements of the $1\times N$ VECSEL array integrated on the VECSEL/photoreceiver chip. The VECSEL array can generate high optical power per element while maintaining fundamental mode oscillation. The diffractive optical element (DOE) is a thin film that collimates and routes the Gaussian beams generated by the VECSEL array. Each RF-modulated collimated optical beam generated by a VECSEL element propagates within the optical substrate and undergoes several reflections in a cavity whose length defined by one of the mirrors assigned to that VECSEL element and the DOE. Every time a beam hits the DOE, a small fraction (5 -10%) of the power of that beam is transmitted through the DOE for detection and amplification by an element of the wideband photoreceiver array that is integrated on the VECSEL/photoreceiver chip, while the remaining large fraction is reflected and routed to for subsequent delayed photodetection. An RF combiner adds (or subtracts) the amplified RF photocurrents to generate the output RF signal. To easily comprehend the ability of the MicroPhotonic RF filter to reconfigure its transfer characteristic, we examine the impulse response of the filter by driving the input with an RF impulse. In this case, each VECSEL element of the VECSEL array generates an optical impulse of power P_0. The optical impulse propagating inside an optical cavity of length L_m is sampled at a time increment of $\sqrt{4L_m^2 + d^2}/\upsilon$, where d is the spacing between the photoreceiver elements, and υ is the speed of light inside the cavity. The power of the reflected impulse after n photodetections is P_0R^n and that of the transmitted impulse is $P_0(1 - R)R^n$, where R is the reflectivity of the DOE. For example, if R = 90% and P_0 = 10 mW, then the power of the optical impulse detected by the first photoreceiver element is 0.1 mW while the power of optical impulse detected by the 16^{th} photoreceiver element is 0.2 mW. By combining the arbitrarily-weighted current impulses, an adaptive Finite Impulse Response (FIR) transversal RF filter is realized. The frequency response of the filter is given by:

$$H(\omega) = \sum_{m=0}^{N-1}\sum_{n=0}^{N-1} \Re K_{VCSEL} P_0 (1-R) R^n G_{m,n} \exp\left[-jn\omega \frac{\sqrt{4L_m^2 + d^2}}{v}\right] \quad (10)$$

where $\Re$ is the photoreceiver responsiveness, $G_{m,n}$ is the current gain of the photoreceiver element (m,n), and $K_{VCSEL} = OMD / I_{RF}$ is the modulation response of the VCSEL elements, with OMD is the optical modulation depth and I_{RF} is the input RF current modulating the VCSEL element. The weights of the current impulses generated by the photoreceiver elements associated with an optical cavity can be changed by adjusting the gains of those photoreceiver elements.

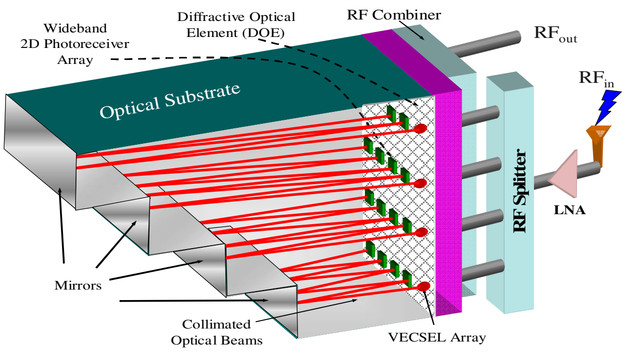

Figure 3. Architecture of the MicroPhotonic RF filter

IV. RESULTS

Figure 4 shows the simulated normalized phase-induced intensity noise versus the laser coherence length for a 4- tap conventional photonic RF notch filter. The unit length of fibre delay line was assumed to be 100 mm. It is shown that when the coherence length of the laser is reduced from 10 m to 40 mm, the noise is reduced significantly over the RF band. Figure 5 shows the normalized maximum phase-induced intensity noise versus the length of the fibre increment delay, for a laser coherence length of 10 m. By increasing the fibre increment delay, the maximum PIIN is reduced. Therefore, to attain a low PIIN, and hence a stable RF filter response, the coherence length of the laser source must be smaller than the delay increment in the filter structure. However, the centre frequency of the filter is inversely proportional to the length of the delay increment. Therefore, for a given laser coherence length, the PIIN can only be reduced in low-frequency (or long delay increment) RF filter structures.

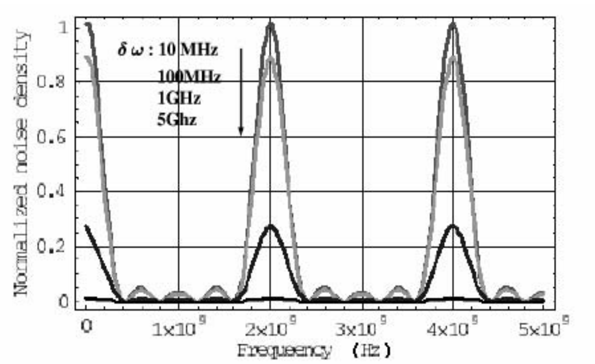

Figure 4 Normalized phase-induced intensity versus the laser coherence length. The length of delay:100mm

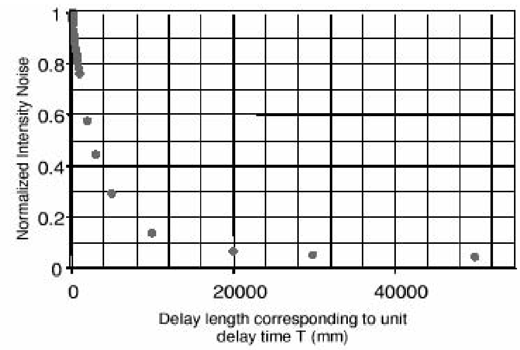

Figure 5. Normalized maximum phase-induced intensity versus delay length corresponding to unit delay time T

Computer simulations were carried out to generate a tunable interference mitigation filter with minimum passband ripples by reconfiguring the gains of the photoreceiver amplifiers of the MicroPhotonic filter. Results were focused on reconfiguring the photonic structure to realise multiple band notch RF filter objectives. Figure 6 shows the frequency responses for a 16-cavity MicroPhotonic filter employing a 16×16 photoreceiver array. The gain profiles were optimized to tune a notch response at centre frequencies around 4.75 GHz while synthesizing two fixed notches at 0.7 GHz and 8.75 GHz. The length of the shortest cavity was assumed to be 1 cm.

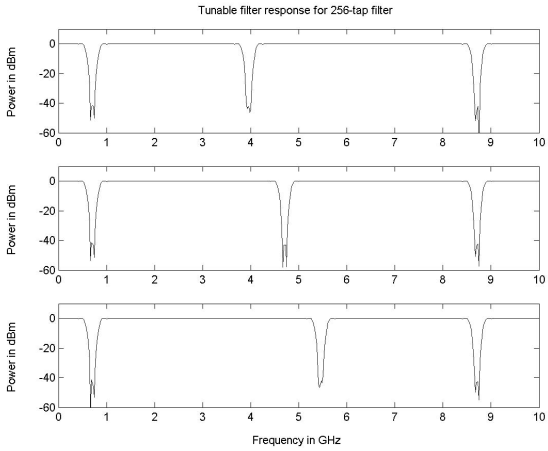

Figure 6. Three-band MicroPhotonic filter responses. Tuning around 4.75 GHz.

Figure 7 shows a spot array generated by launching four, 500 μm diameter collimated optical beams into a custom-made optical cavity of length 20 mm and mirrors of reflectivities 95% and 100%. This proves the capability of the MicroPhotonic RF filter to generate a spot array of delayed RF-modulated beams. It is obvious from Figure 7 that the beams diverge as they propagate within the cavities, and that a DOE film is critical for generating longer RF delays. This issue will be addressed in future publications.

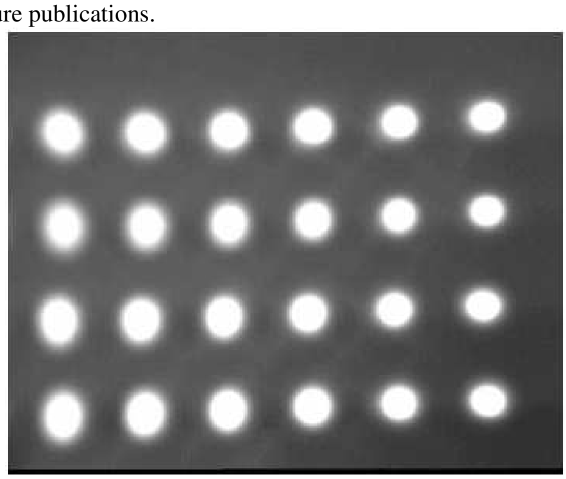

Figure 7. 4×6 spot array generated within a custom-made 20mm long optical substrate

V. CONCLUSION

The impact of optical coherence on the performance of optical fibre based FIR filter has been studied in detail. Photonic signal processors using long-coherence-length optical sources generate phase-induced intensity noise which causes substantial instability to the RF resposnse. To suppress the phase-induced intensity noise in the photonic RF filter, a novel MicroPhotonic broadband RF interference mitigation processor that generates true-time RF delays to perform finite impulse response transversal filtering, has been presented. The novel MicroPhotonic structure integrates a photoreceiver array, a Vertical Cavity Surface Emitting Laser (VCSEL) array, and a multi-cavity optical substrate to realize a low-cost adaptive wideband RF interference mitigation filter. Experiment results demonstrated the generation of many true-time delayed optical beams and computer simulation results verified the capability of the MicroPhotonic processor to realize a high-resolution, multiband tunable interference mitigation filter.

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