Optical architecture for programmable filtering of microwave signals

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We present a new optoelectronic architecture, based on parallel canceled delay lines, that performs programmable filtering of microwave signals. The new architecture can process optically carried microwave signals over frequency bandwidths as large as 20 GHz, with a time–frequency product up to 10^3. The operating principle of this structure is detailed, followed by the preliminary experimental demonstration at 1.2 GHz of a 40-dB rejection filter. © 1996 Optical Society of America

The availability of optoelectronic components operating in the multigigahertz domain (up to 20 GHz) is attractive from the perspective of optical processing of microwave signals.[1–8] Owing to their inherent parallel processing capabilities, optoelectronic architectures are well suited for implementation in radar and electronic warfare systems with basic functions such as spectrum analysis, adaptive filtering, and correlation. In this Letter we propose and experimentally demonstrate a new optoelectronic programmable filter in which time delays are generated by a diffractive mirror (DM) and parallel weighting is obtained with a liquid-crystal spatial light modulator (LC SLM).

A parallel filter optimizes the detection in a signal $x(t) = S(t) + N(t)$ of a given signal $S(t)$ with duration T in the presence of a stationary noise $N(t)$ or permits rejection of jammers from detected signals. Matched filtering is a particular case in which the signal-to-noise ratio is maximized in the presence of white noise. The output $y(t_0)$ of the filter at time t_0 is expressed as

$$y(t_0) = \int_{t_0-T}^{t_0} x(t)S(t - t_0)\mathrm{d}t\,. \tag{1}$$

These signals are often processed in a sampled form by the use of a delay line made with n coupling elements separated by time delay τ_i, yielding $x(t), \ldots x(t - k\tau_i), \ldots x(t - n\tau_i)$. Each of these samples can be weighted with a normalized weight α_k to provide the output $\alpha_k x(t - k\tau_1)$, where α_k is given by $\alpha_k = S[(n - k)\tau_i]/|S_{\max}|$. $S_{\max}$ is the maximum value of $S(t)$ over time duration T. In this case Eq. (1) becomes a discrete sum of products, and matched filtering reduces to a weighting method. If we sum these $(n + 1)$ weighted outputs at time t_0, we obtain, after the following change of coordinates $T = n\tau_i$ and $t_0 - k\tau_i = t_k$, a term proportional to

$$\sum_{k=0}^{n} x(t_k)S[t_k - (t_0 - T)]\,. \tag{2}$$

Compared with Eq. (1), this term appears as the sampled output $y_s(t_0 - T)$ of the matched filter at time $t_0 - T$. The time delay τ_i represents the sampling period and $B = 1/2\tau_i$ the processed frequency bandwidth. Digital electronic delay lines permit processing of signals with a rather large number of samplings (up to 10^2–10^3) but with a frequency bandwidth B limited to the low and intermediate frequencies (100 MHz–1 GHz).[8] Therefore processing of the whole 20-GHz bandwidth is not possible and is done successively over intervals of a few gigahertz. On the other hand, optical fiber delay lines present the advantage of enabling one to process signals over a large frequency bandwidth, but they are generally implemented with a reduced number of sampling points (10–100) (Refs. 2–6), and the weighting is difficult to obtain. Therefore we propose an optical architecture of a programmable filter that could provide a large sample number of approximately 10^3 and that can process signals over a frequency bandwidth as large as 20 GHz.

The operating principle of this filter is shown in Fig. 1. A cw laser diode of wavelength λ is coupled into an integrated optic amplitude modulator, excited by a signal $x(t)$, in the microwave range. The outcoming beam is then an optical carrier of this signal $x(t)$. It is expanded and reflects off a DM, which operates in a Littrow geometry. Such a beam is, for instance,

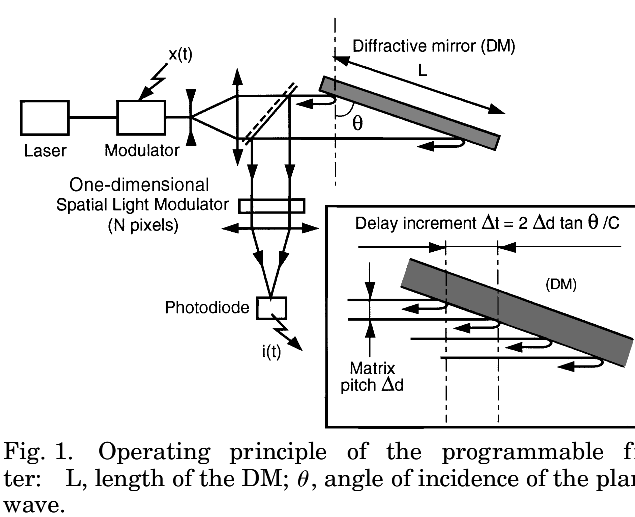

Fig. 1. Operating principle of the programmable filter: L, length of the DM; θ, angle of incidence of the plane wave.

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a classical blazed grating or, as proposed in Ref. 10, a Bragg grating recorded in a photopolymer material. This reflected beam, extracted with a beam splitter, passes through a one-dimensional SLM of N pixels, which can be, for instance, a LC SLM. Finally, the channeled beam is focused onto a photodiode. According to the operating principle of the DM, the elementary incident plane waves that diffract on two successive steps of the grating have an elementary path-length difference of λ, corresponding, for the carried signal $x(t)$, to an elementary time delay of λ/c (where c is the velocity of light). Therefore the incident plane wave that diffracts on the mirror aperture has a maximum path-length difference of $2L\sin\theta$ (Fig. 1) corresponding to a maximum time delay $T = 2L\sin\theta/c$. The pixels of the SLM have a center-to-center spacing Δd and provide, through a control voltage, a weighting of the amplitude of the light field with coefficients α_k. Because the DM diffracts a plane wave ($k\omega\Delta t/2\pi$ is an integer and $\Delta t = 2\Delta d\tan\theta/c$ is the delay increment), where $\Delta t = 2\Delta\mathrm{d}\tan\theta/c$ is the delay increment), every k channel of the SLM transmits an optical field E_k that is expressed, for a low modulation ratio m, as $E_k = \alpha_k E_0\{1 + j\exp j[mx(t - k\Delta t]\}\exp[j(\omega t + \phi_k)]$. The optical field is an optical carrier of the delayed signal $x(t - k\Delta t)$. E_0 is the amplitude of the optical field associated with the diffracted plane wave. The model developed here also takes into account possible phase aberrations ϕ_k induced by the DM and the SLM.

When the coherence time t_c of the source is smaller than the increment $\Delta t (t_c \ll \Delta t)$, for instance with a superluminescent diode, the integration on the surface S of a detector with responsivity Γ amounts to an incoherent summation by a lens (with focal length F) of all the intensities provided by each pixel (Fig. 1). The photodiode then delivers the photocurrent

$$i(t) = \Gamma\int_s\left\langle\sum_{k=0}^{N}|E_k|^2\right\rangle\mathrm{d}S = \Gamma S|E_0|^2\sum_{k=0}^{N}|\alpha_k|^2\times|1 + j\exp[jmx(t - k\Delta t)]|^2. \tag{3}$$

$\langle\ \rangle$ represents time averaging over the response time of the photodiode. Equation (3) reduces, for $m \ll 1$, to

$$i(t) \approx 2\Gamma S|E_0|^2\sum_{k=0}^{N}|\alpha_k|^2 - 2m\Gamma S|E_0|^2 \times\sum_{k=0}^{N}|\alpha_k|^2 x(t - k\Delta t). \tag{4}$$

The first term in relation (4) is a constant bias. The second one is the result of matched filtering of the signal $S(t)$ [term (2)] if we choose the coefficient α_k so that $|\alpha_k|^2 = S(T - k\Delta t)$. If the coherence source is large ($t_c \gg \Delta t$) we have to consider a coherent optical summation of all the emerging channels. When the photodiode diameter $\varnothing$ is small compared with the highest spatial frequency provided by the SLM, i.e., $\varnothing \le \lambda F/N\Delta d$, then the photocurrent is expressed as

$$i(t) = \Gamma\int_S\left\langle\left|\sum_{k=0}^{N}E_k\right|^2\right\rangle\mathrm{d}S, \tag{5}$$

which leads, for $m \ll 1$ and $\phi_{kk'} = \phi_k - \phi_{k'}$ to

$$i(t) = 2\Gamma S|E_0|^2\sum_{k=0}^{N}|\alpha_k|^2 + 4\Gamma S|E_0|^2\sum_{k=0}^{N}\sum_{k'\ne k}\alpha_k\alpha_{k'} \times\cos\phi_{kk'} - 2m\Gamma S|E_0|^2\sum_{k=0}^{N}\beta_k x(t - k\Delta t), \tag{6}$$

$$\beta_k = |\alpha_k|^2 + \sum_{k'\ne k}\alpha_k\alpha_{k'}(\cos\phi_{kk'} + \sin\phi_{kk'}). \tag{7}$$

It corresponds to a spatial filtering when the on-axis plane-wave component is taken into account. One can notice that Eq. (6) is equivalent to relation (4), except for supplementary terms of interference between the pixels of the SLM. The first two terms in Eq. (6) correspond to a continuous background. The last one is the result of matched filtering of the signal $S(t)$ if we choose the coefficient β_k so that $\beta_k = S(T - k\Delta t)$. In this case weighting coefficients α_k of every pixel k are deduced from the set of Eqs. (7). Furthermore, when the photodetector size is increased to $\varnothing \ge \lambda F/\Delta d$ with $t_c \gg \Delta t$, then all the spatial frequencies of the image displayed on the SLM are collected and averaged by the photodiode. In this case the contribution of the terms $\phi_{kk'}$ vanishes and the modulated photocurrent reduces to the incoherent summation of relation (4). The response time of the proposed adaptive filter is determined mainly by the response time T_r of the LC SLM. Ferroelectric or chiral smectic LC SLM's exhibit switching time in the range of 10–100 μs but with poor analog gray-scale performance. Conversely, nematic LC SLM's classically provide 256 gray levels but with the drawback of response times in the range of 10–100 ms. In order to meet radar or electronic wavefare systems' requirements in terms of adaptive processing speed in the range of 10 ns to 10 μs it would be necessary to use multiple-quantum-well SLM's[10] or to take advantage of the high resolution of LC SLM's. Their resolution (up to $10^3 \times 10^3$) allows us to extend our concept to a two-dimensional architecture in which a $N \times P$ pixel LC SLM provides in parallel P columns of N weightings $\alpha_{k,j}$ $(1 \le j \le P, 1 \le k \le N)$. Each one of the P channeled beams is focused onto one of the photodiodes of a P detector array, by use, for instance, of a cylindrical lens. In this case adaptive processing time is approximately T_r/P and could match system specifications for $P \approx 10 - 100$. As a proof of concept a filter is implemented with a cw laser diode (60 mW at 840 nm) with a

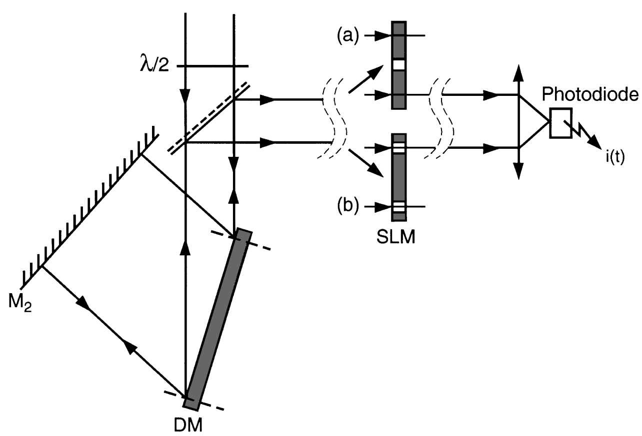

Fig. 2. Implementation of the adaptive filter: $L = 58$ mm, DM = 1800 lines/mm, $F = 120$ mm.

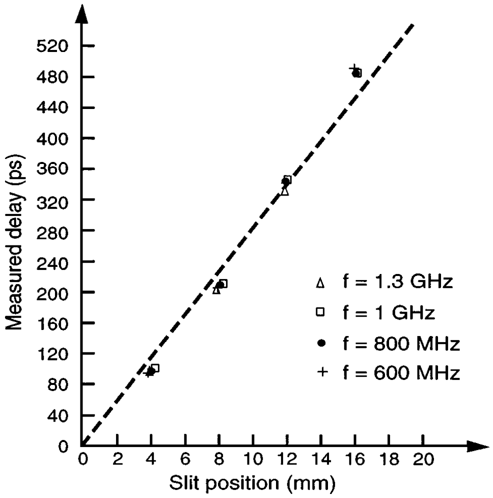

Fig. 3. Time delay experienced by the optical carrier: whatever the frequency used in the range 0.6–1.3 GHz, the delay experienced by the signal $S(t)$ across the aperture varies linearly with the position of the moving slit from one edge (0) of DM to the other one (20 mm). The maximum value is ≈0.5 ns.

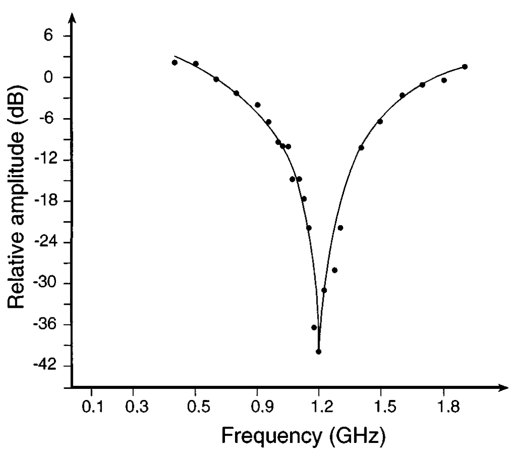

Fig. 4. Rejection filter response obtained with a two-slit figure displayed on the SLM: the relative amplitude is given by the ratio $y_s(f,t)/y_1(f,t)$. The signal $y_1(f,t)$ corresponds to the beam transmitted by only one of the two slits.

large coherence time ($t_c \gg \Delta t$). It is coupled through a polarization-maintaining fiber into an integrated-optic Mach–Zehnder modulator excited by a microwave signal $x(t)$. The outcoming beam is expanded and reflects off the DM, which operates with a Littman–Metcalf geometry (Fig. 2). Because the DM is polarization selective, it is necessary to use a retardation plate in order to maximize the optical power of the diffracted beam. Then the beam passes through a video-controlled (256 gray levels) LC SLM (320 × 264 pixels of area 56 μm × 44 μm with a 80-μm matrix pitch) and is detected by a Si avalanche photodiode.

In order to verify the delays experienced by a signal $x(t)$ in the range of 0.6–1.3 GHz, emerging light is detected through a 1-mm slit, which is moved across aperture D of the beam [(a) in Fig. 2]. The result shows that whatever the frequency used, the signal experiences a delay that varies linearly with the position of the slit. The maximum delay T is constant with frequency and equal to 480 ps (Fig. 3). As a proof of concept, the maximum delay obtained allowed us to implement a simple rejection filter over a 2-GHz bandwidth. The modulator is fed with a microwave signal at frequency f, and an image of two slits is displayed on the SLM [(b) in Fig. 2]. These slits define two channels corresponding to the two edges of the DM, with the relative maximum time delay T. The diameter of the detector (80 μm) is large compared with the dimension $\lambda F/N\Delta d \approx 4$ μm ($F = 120$ mm, $N\Delta d = 25.6$ mm), which has to be considered here because only the two extreme pixels are taken into account. In this case the modulated photocurrent is expressed as in relation (4) and reduces to $y_s(f,t) = \cos 2\pi ft + \cos 2\pi f(t - T)$. For a given frequency f_0 corresponding to $2\pi f_0 T = \pi$, this modulated photocurrent vanishes, which means that we obtain a rejection filter that cancels the frequency f_0 of the signal $x(t)$. Therefore the filter response (Fig. 4) shows a 40-dB rejection of signal $y_s(f_0, t)$ at $f_0 = 1.2$ GHz.

To summarize, we have proposed a new programmable optical architecture based on parallel tapped delay lines generated by a diffractive mirror in the Littrow configuration. Channeling and weighting is provided by a LC SLM, and according to the principle described above this architecture can simultaneously process microwave signals over frequency bandwidths as large as 20 GHz. A 40-dB rejection filter was implemented at 1.2 GHz. According to these preliminary results it is realistic to extend these concepts to the realization of an $N = 10^2 - 10^3$ channel filter. Performance of such an architecture in a multijammer environment and further signal-processing functions will be investigated.

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