Appl. Phys. B 68, 1027–1030 (1999) / DOI 10.1007/s003409900037

Applied Physics B
Lasers
and Optics

Photo-EMF-based adaptive detectors as optimal photodetectors for detection of light-pattern displacements

S. Stepanov

INAOE, Ap. Post. 51 y 216, Puebla, 72000, Mexico

Received: 8 December 1998/Revised version: 1 February 1999/Published online: 12 April 1999

Abstract. It is shown that non-steady-state photo-EMF-based adaptive photodetector operates like an optimal detecting medium when detection of a general spatial shift of a complicated light pattern is needed. This detecting medium can be considered as some spatial distribution of photo-induced p–n junctions matched with the original light pattern and its sensitivity is limited basically by the thermal (Johnson) noise of the detector volume itself.

PACS: 72.40.+w; 42.70.Nq; 42.79.Pw

Conventional photodetectors, such as photoelectron multipliers or photodiodes, detect the light intensity averaged over the whole photosensitive area of the device. As a result, when used for detection of phase modulation in a signal laser beam (S), the light intensity in one particular point of the interference pattern between the signal and the reference (R) waves can be detected only. If one has two similar simple interfering wavefronts (for example plane or Gaussian) combined via a conventional beam-splitter (Fig. 1a), there is no problem. The detected area can be spread through the whole signal-beam cross section and the signal-beam power (which is usually the lower one) is not lost. When, however, there is a need to detect general phase modulation in a complicated wavefront (for example a speckle-like one, which is reflected from a vibrating rough surface), one can not do this efficiently using conventional photodetectors and beamsplitters. It is clearly because of spatially random distribution of an average phase shift between the signal and the reference beams through the interference pattern. The angular aperture of the light-collecting lens system corresponding to one speckle spot is usually used here only [1]. This results in big losses of the signal-beam power and finally in strong reduction of the output signal combined with environmentally induced random temporal fluctuations in its sign and amplitude.

About a decade ago a nonconventional type of photodetector [2], based on the non-steady-state photo-EMF effect [3, 4] was proposed for efficient detection of the optical phase modulation under the conditions mentioned above, Fig. 1b. Originally this device was used as an "adaptive" photodetector which possesses the property to compensate for com-

This paper is dedicated to Prof. E. Krätzig whom the author respects deeply as a really prominent researcher, teacher, and a person of high character.

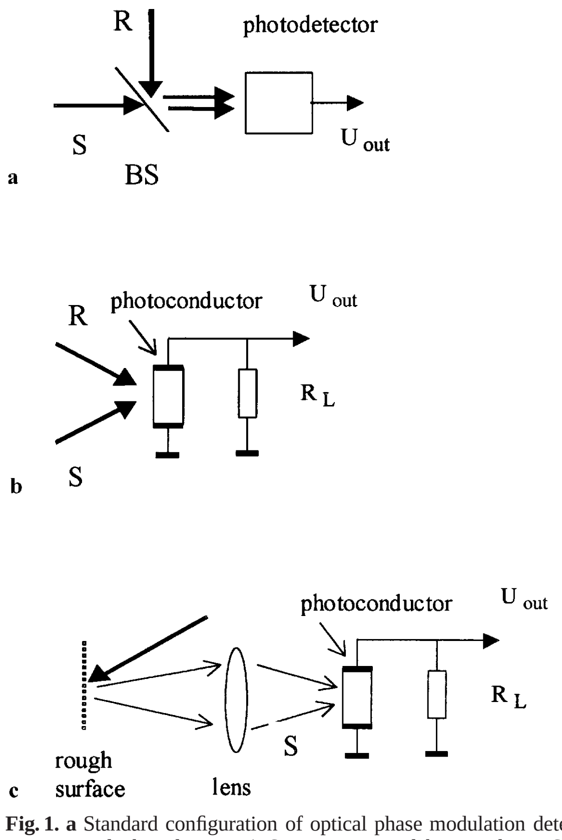

Fig. 1. **a** Standard configuration of optical phase modulation detection with conventional photodetector (BS is conventional beam-splitter, S and R are the signal (phase modulated) and the reference beams, respectively, and U_{out} is the output electrical signal). **b** Interferometric (with a reference beam) configuration for detection of optical phase modulation with photo-EMF based adaptive photodetector (R_L is the load resistor). **c** Referenceless configuration for detection of fast spatial displacements of speckle-like light patterns (for example reflected by a rough vibrating surface) via photo-EMF-based adaptive photodetector

plicated wavefronts, for relatively slow environmental phase drifts in them, and also for amplitude noise of the laser. Recently [5], application of the photo-EMF-based GaAs adaptive detectors for efficient detection of the laser-induced ultrasonic in moving (with an average speed up to 1 m/s) real objects with a rough surface was demonstrated. We also demonstrated experimentally [6] that these photodetectors can be used for detection of the transverse displacements of rough surfaces, and transverse displacements of the irregular 2D speckle-like patterns in general (Fig. 1c). Later, a similar referenceless configuration (which was also discussed in [7]) was used in [8] for detection of the transverse surface displacements produced by the laser ultrasonic waves.

Below we show that the photo-EMF-based photodetectors are, in fact, "optimal" for detection of such transverse displacements of complicated spatial light-intensity distributions. This means that they give the maximum possible output signal in response to these particular changes of the pattern shape and ensure maximum signal-to-noise ratio (SNR) in detection of these shifts.

Let us consider for simplicity that within some spatial interval (0, L_x) we have an initial one-dimensional intensity distribution $I(x)$ biased by a relatively strong noncoherent light intensity I_0 ($I_0 \gg I(x)$) - see Fig. 2a. Here we are not interested in detection of this complicated light distribution itself, but in detection of a small displacement of this pattern along the x axis only. The spatial shift of this pattern by a distance Δx can obviously be described by the appearance of an additional small (zero-average if $I(0) = I(L_x)$, or $I(0) = I(L_x) = 0$ in particular, Fig. 2a) light pattern:

$$\Delta I(x) = -\frac{\partial I(x)}{\partial x}\Delta x\,. \qquad (1)$$

See Fig. 2b. Let us assume, that for detection of this light-intensity distribution $\Delta I(x)$, we design an optimised distributed detection system in the volume of a short-circuited photoconductive sample with the interelectrode spacing L_x. By this detecting system we mean something like a continuous irregular sequence of p–n junctions of different height, which are "frozen in" in our detecting medium. It is assumed that the shape of this detecting pattern is matched to detect the light distribution $\Delta I(x)$ in some optimal way. This structure can be described by some spatial distribution of the electric potential $\varphi(x)$, and the electric field, which is associated with it, obviously equals $E(x) = -\partial\varphi(x)/\partial x$. In this sense, the conventional photodiode is characterised by very simple electric potential distribution – a simple potential jump in the area of p–n junction associated with some maximum of the electric field there (see, for example, Fig. 10 in Chapt. 2 of [9]).

As is known from the literature [4, 10], the electric response (i.e. the short-circuit current density j) of this electric field profile in the volume of the photoconductor material to the appearance of an additional light distribution $\Delta I(x)$ is equal to the local drift current density averaged over the interelectrode spacing:

$$j = \frac{1}{L_x}\int_0^{L_x} \mathrm{d}x E(x)\Delta\sigma(x) = \frac{1}{L_x}\int_0^{L_x} \mathrm{d}x E(x) A\Delta I(x)\,, \qquad (2)$$

where $\Delta\sigma(x) = A\Delta I(x)$ is the additional photoconductivity of the sample due to $\Delta I(x)$ (A is a coefficient of proportionality). The diffusion component of the current density and that of the displacement one do not contribute to the total current through the structure because of the above-mentioned boundary conditions for $I(x)$, and because of the potential nature of the electric field, respectively. Note also, that in (2) we assumed linear proportionality between the local level of illumination and the photoconductivity of the sample. This is obviously justified in a case when the transport lengths of the photocarriers (drift and diffusion ones) are smaller than the characteristic scale of the spatial variations in $\Delta I(x)$.

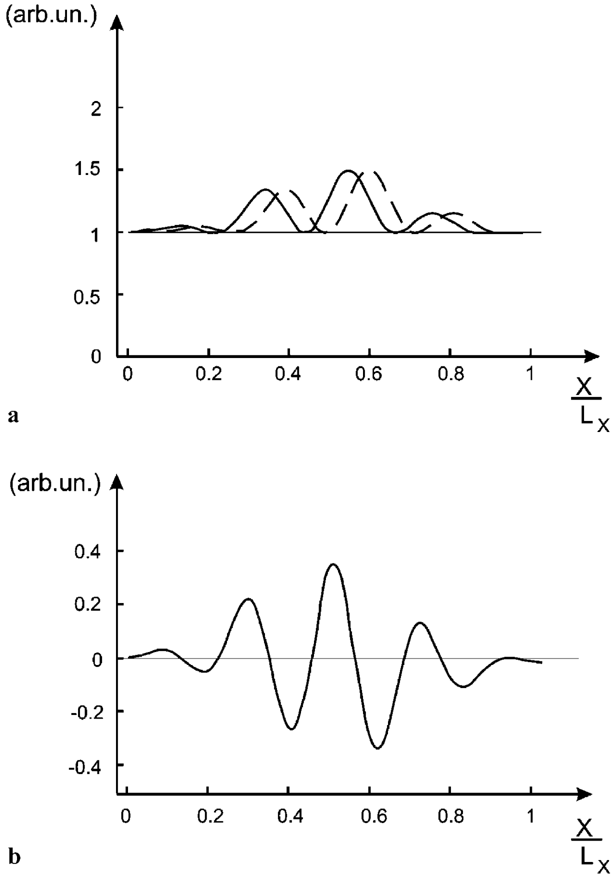

Fig. 2. **a** Some examples of the normalised initial – $[I_0 + I(x)]/I_0$ *(solid line)*, and shifted – $[I_0 + I(x - \Delta x)]/I_0$ *(dashed line)* one-dimensional light-intensity distributions. **b** Normalised additional light intensity $\Delta I(x)$ associated with the introduced above spatial shift of the light pattern $I(x)$

It is well known, that for a limited value of $\int_0^{L_x} \mathrm{d}x|E(x)|^2$ the integral in the right-hand side of (2) (and finally the output electric current through our detecting structure) is maximised when:

$$E(x) \propto \Delta I^*(x) \propto \frac{\partial I^*(x)}{\partial x}\,. \qquad (3)$$

Note that in addition to producing the maximum output, the same distribution of the electric field $E(x)$ (3) acts like an optimal filter [11] – i.e. it gives the minimum error rate (i.e. the maximum SNR) in recognition of the input signal $\Delta I(x)$. Note also that since the intensity distribution $\Delta I(x)$ is obviously described by a real function, we can also remove complex conjugation from the right-hand side of (3). From here it follows that the electric potential profile in the optimal detection structure is simply to copy the profile of the initial (unshifted) light pattern ($\varphi(x) \propto I(x)$).

On the other hand, the diffusion mechanism of optical recording in photorefractive crystals (see for example [12]), which, in particular, is in charge of the photo-EMF signal formation [3, 4], gives the steady-state (i.e. under continuous illumination) space-charge electric field profile, which is practically needed:

$$E_{SC}(x) = -\left[\frac{\partial I(x) + I_0}{\partial x} \Big/ I(x) + I_0\right] \frac{k_B T}{e} \approx -\frac{k_B T}{e I_0}\left(\frac{\partial I(x)}{\partial x}\right) . \quad (4)$$

Here k_B is the Boltzmann constant, T is the absolute temperature, e is the electronic charge, and the electron type of photoconductivity is accepted. As a result, the photo-EMF current response (2) in this case equals

$$j = \frac{1}{L_x} \int_0^{L_x} dx E_{SC}(x) A \Delta I(x) = \sigma_0 \frac{k_B T}{e} \frac{\Delta x}{L_x} \int_0^{L_x} dx \left(\frac{\partial I(x)}{\partial x} / I_0\right)^2 , \quad (5)$$

where $\sigma_0 = A I_0$ is the average photoconductivity of the sample. From (3)–(5) it is clear that our photo-EMF configuration obviously acts like the previously discussed spatially distributed detecting media optimised for detection of the displacement of this particular initial light pattern $I(x)$. The necessary "frozen-in" electric potential profile (and the corresponding space-charge electric field) in the photoconductor volume results from diffusion of the nonuniformly photoexcited mobile carriers which is followed by their retrapping.

Note that the output signal presented by (5) is a direct generalisation of the photo-EMF response obtained earlier in [3, 4] for a sinusoidal periodically oscillating light pattern. In the present analysis we considered, however, the arbitrary initial intensity profile $I(x)$ and neglected, for simplicity, influence of the carrier diffusion spreading on the photoconductivity pattern. In fact, the latter effect can reduce the contrast of the nonstationary (i.e. shifted or vibrating) carrier pattern at high spatial frequencies ($K \geq L_D^{-1}$, where L_D is the diffusion length of photocarriers) and, finally, the amplitude of the photo-EMF output signal. In some way, it acts like a low-pass spatial frequency filter in our detector. Neglecting this effect allowed us to consider that the carrier pattern simply copies the profile of the light pattern (5), which clearly simplified the above analysis.

Note also that the real photo-EMF current observed in this experiment (fast displacement of the pattern by a distance Δx) is, of course, the transient one [3, 4]. After the characteristic dielectric relaxation time $\tau_{di} = \varepsilon\varepsilon_0/\sigma_0$ it decays practically to zero level because of the space-charge field redistribution to a new (shifted) position of the light pattern ($I'(x) = I(x - \Delta x)$). Indeed, in this new steady-state $E'_{SC}(x) \propto \partial I'(x)/\partial x$, and the photo-EMF current ($\propto \int_0^{L_x} dx E'_{SC}(x) A I'(x)$) equals zero again.

We analysed above the case of a spatial displacement of irregular one-dimensional pattern. A similar approach can also be used for formal description of detection of phase modulation of one of the interfering coherent waves with the photo-EMF adaptive detector (Fig. 1b). Here, if the spatial frequency contents of two interfering beams are noticeably poorer than the average spatial carrier frequency, the shift of the carrier frequency (due to phase modulation in one of the beams) can be approximated by a total shift of the interference pattern. In this approximation the above analysis is applicable to this interferometric configuration practically directly. This means that the photo-EMF-based adaptive photodetectors are optimal for detection of a general phase modulation in complicated wave-fronts as well. However, some reduction of the output photo-EMF signal to compare with the case of simple plane waves is possible. For example, in [13] it was observed experimentally that substitution of the plane signal wave in the interferometric configuration (Fig. 1b) by a speckle-like one (with the same average intensity) reduces the output photo-EMF signal (by a factor ≈ 2). Since these experiments were performed with equal average intensities of the signal and the reference beams, this drop in the signal can be explained basically by reduction of the local contrast of the interference pattern due to non-equal beam intensities. One can expect, however, that for some observable difference in the average light intensities ($I_S \ll I_R$) the interferometric detection configuration can be not too sensitive to the structure of the signal wave.

Detection of displacements of really 2-D speckle-like pattern (for example in a referenceless configuration given in Fig. 1c) obviously needs more complicated analysis. However, it is clear that the main feature of the behaviour considered above, i.e. the "matched" character of the 2D photo-induced detector structure is the same as in the 1D case which was considered here. Indeed, every speckle spot in the initial light pattern will be surrounded by a radially symmetrical distribution of the space-charge field, directed from the center of the spot outside for the electron type of photoconductivity. Synchronous displacement of all speckle spots into one particular direction clearly results in overlapping of all of them with the areas where the space-charge electric field has the same direction. As a result, in accordance with the nature of the photo-EMF signal formation [3, 4], this will produce efficient total current through the structure along the direction of the displacement. Even without a strict formal analysis this allows us to state that in a 2D case the photo-EMF detectors also ensure some matched detection of the general displacements of the speckle-like light patterns.

In conclusion, let us discuss shortly the main factors limiting the sensitivity of these photodetectors. Earlier in [14] it was shown that for maximum possible contrast ratio of the regular sinusoidal interference light pattern ($m \approx 1$) and optimal fringe spacing $\Lambda = 2\pi L_D$ the thermal (Johnson) noise of the sample is approximately equal to the shot noise, which is also generated in the photo-EMF configuration. The latter is observed here even without external dc voltage bias because of the diffusion-induced space-charge electric field $E_{SC}(x)$ within the sample volume. In the above consideration we assumed, however, an approximation of short carrier transport length ($\Lambda \gg 2\pi L_D$). This clearly ensures reduction of the diffusion space-charge field (due to bigger fringe spacing) and finally reduction of the relative contribution of the shot noise. This means that in the accepted approximation the detection configuration under consideration is basically the thermal-noise-limited one.

Acknowledgements. This work is performed within the framework of CONACyT (Mexico) Project G255330A.

References

1. C.B. Scruby, L.E. Drain: *Laser Ultrasonics: Techniques and Applications* (Adam Hilger, Bristol 1990)
2. S.I. Stepanov, I.A. Sokolov, G.S. Trofimov, V.I. Vlad, D. Popa, I. Apostol: Opt. Lett. **15**, 1239 (1990)
3. G.S. Trofimov, S.I. Stepanov: Sov. Phys. Sol. State **28**, 1559 (1986)
4. M.P. Petrov, I.A. Sokolov, S.I. Stepanov, G.S. Trofimov: J. Appl. Phys. **68**, 2216 (1990)
5. P.V. Mitchell, S.W. McCahon, M.B. Klein, T.R. O'Meara, G.J. Dunning, D.M. Pepper: Tech. Digest of *Photorefractive Materials, Effects and Applications* Conference (Aspen Lodge, USA 1995) p. 432–434
6. N.A. Korneev, S.I. Stepanov: J. Mod. Opt. **38**, 2153 (1991)
7. M. Klein, D. Bacher: Proc. SPIE **3411**, 53 (1998)
8. N. Korneev, P. Rodriguez, S. Stepanov: Tech. Digest of CLEO'97 Conference (Baltimore, USA 1997) p. 47
9. S.M. Sze: *Physics of Semiconductor Devices* (Wiley, New York 1981)
10. M.A. Lampert, P. Mark: *Current Injection in Solids* (Academic Press, New York 1970)
11. L.E. Franks: *Signal Theory* (Prentice-Hall, Englewood Cliffs, N.J. 1969)
12. M.P. Petrov, S.I. Stepanov, A.V. Khomenko: *Photorefractive Crystals in Coherent Optical Systems* (Springer, Berlin, Heidelberg 1991)
13. M.L. Arroyo Carrasco, P. Rodriguez Montero, S. Stepanov: Opt. Commun. **157**, 105 (1999)
14. S.Stepanov: Appl. Opt. **33**, 915 (1994)