Effect of non-ideal beamsplitters in THz electro-optic detectors

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***Abstract*—We extend a mathematical investigation of the noise in THz electro-optic detectors by considering the non-ideal properties of beam splitters in addition to non-ideal polarisers. It is found that the non-ideal properties of typical beam splitters can result in an unwanted noise floor in certain detectors.**

I. Introduction and Background

BALANCED THz detection systems developed for electro-optic sampling should ideally have zero background noise from laser power fluctuations as both photodiodes will measure the same change. This is not true in practice due to non-ideal polarisers and an imperfect input laser causing polarisation imbalances [1, 2].

Here we extend an existing mathematical treatment [1] to include non-ideal beam splitters. We will show that these imperfect beam splitters can create balancing issues due to slightly different transmission and reflection of s and p polarised light. This results in one photodiode receiving more light when the laser power fluctuates, ruining the balance and creating a noise floor that makes THz measurements less sensitive. We investigate this effect for different electro-optic detectors. The first case shown in Fig. 1 is used to describe the mathematics in this presentation.

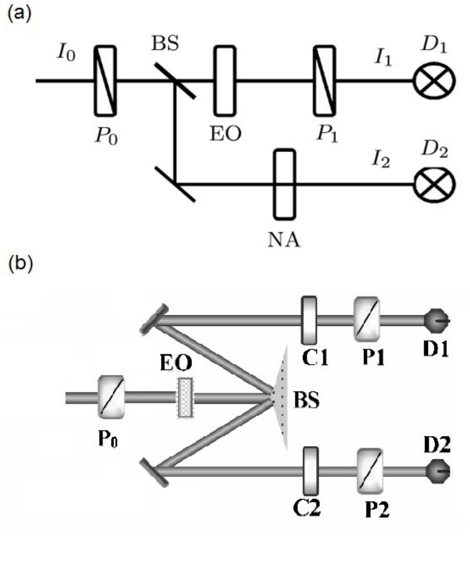

Fig. 1. Two of three studied electro-optic detector systems from [1] and [2]. P_0 and P_1 are polarisers, BS—Beamsplitter, NA—Neutral attenuator, D1 and D2—Photodiodes, EO—Electro-optic crystal, C1 and C2—Phase compensators. I_0 is the laser intensity.

A. Example EO detector calculation

We construct two non-ideal beam splitter matrices in (1) where the electric field transmittance and reflectance of the s and p polarisations are given by four constants C_{pt}, C_{st}, C_{pr} and C_{sr}. All four constants are equal to 1 for an ideal beam splitter.

$$\begin{aligned} BS_t &= \frac{1}{\sqrt{2}}\begin{pmatrix} C_{pt} & 0 \\ 0 & C_{st} \end{pmatrix} \\ BS_r &= \frac{1}{\sqrt{2}}\begin{pmatrix} C_{pr} & 0 \\ 0 & C_{sr} \end{pmatrix} \end{aligned} \tag{1}$$

Adapting the mathematics in [1] to obtain (2), we calculated the laser electric field at each detector D_1 and D_2, incorporating the constructed non-ideal beamsplitter matrix in (1). The results for D_1 are shown.

$$\begin{pmatrix} E_x \\ E_y \end{pmatrix} = P_1 M_{E_O} \frac{1}{\sqrt{2}} \begin{pmatrix} C_{pt} & 0 \\ 0 & C_{st} \end{pmatrix} P_0 \begin{pmatrix} E_{x0} \\ E_{y0} \end{pmatrix} \tag{2}$$

Here M_{E_O}, P_0 and P_1 represent the electro-optic crystal and polarisers as detailed in [1].

We convert the laser electric field in (2) to power at each detector D_1 and D_2 shown in equations (3) and (4) .

$$\begin{aligned} I_1 = {} & P_x(P_y \cos^2\frac{\delta_s}{2} + P_x \sin^2\frac{\delta_s}{2})\frac{I_{x0}}{2}{C_{pt}}^2 \\ & + P_y(P_x \cos^2\frac{\delta_s}{2} + P_y \sin^2\frac{\delta_s}{2})\frac{I_{y0}}{2}{C_{st}}^2 \end{aligned} \tag{3}$$

$$I_2 = \frac{1}{2}\gamma(P_x I_{x0} {C_{pr}}^2 + P_y I_{y0} {C_{sr}}^2) \tag{4}$$

Here δ_s is the static birefringence of ZnTe and γ is the neutral attenuator constant.

By taking the difference of the detectors and assuming a small laser fluctuation of ΔI_{x0} and ΔI_{y0} and that the beam splitter constants are similar we reach the corresponding noise fluctuation (5).

$$\nu_{noise} \approx \frac{{C_{st}}^2}{2} P_x P_y \cos^2\frac{\delta_s}{2}(\Delta I_{y0} - \frac{I_{y0}}{I_{x0}}\Delta I_{x0}) \tag{5}$$

Equations [2]-[5] can be simplified to give the corresponding ideal beam splitter equations in [1].

For the two detectors in [1], given by the type shown in Fig 1. a), the noise is observed to be altered by a scaling factor related to C_{st}. Since $C_{st} \approx 1$ for a 50/50 typical beam splitter, these two detectors will experience almost no change to the noise floor from imperfections in the beam splitter.

Considering the newly designed detector in Fig 1. b), the I_1 and I_2 laser powers are equal due to the symmetric nature of the setup. Hence for an ideal beam splitter, we get:

$$\nu_{noise} = 0 \tag{6}$$

For a non-ideal beam splitter, the symmetry of I_1 and I_2 is broken resulting in a DC offset that fluctuates with laser power, thus creating a noise floor.

II. RESULTS

By comparing the ideal beam splitter equations in [1] with (5), it was shown that the design in Fig 1. a) and the other similar design listed in [1] are insensitive to the non-ideal properties of the beam splitter.

For the new detector design in Fig 1. b), the system was found to have zero noise due to laser fluctuations in the ideal beam splitter case and had an introduced noise floor when using an imperfect beam splitter. These results are to be expected due to the high symmetry of the system [2].

These results do not take into account the wavelength dependence. This would make components like the beam splitters and phase compensators less ideal and hence potentially raise the noise floor. Also, it is assumed that for the highly symmetric system, that the compensators and polarisers have identical optical properties. Small deviations in C1, C2, P1 and P2 could increase the system noise [2].

III. CONCLUSION

For an electro-optic detector system with the lowest noise floor, a highly symmetrical beam splitter in conjunction with the detector described in [2] should be used. Upgrading the beamsplitter in the other THz detectors would provide only minimal improvements.

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