Simple device for continuous angle-of-incidence selection in ultrafast experiments

F. Kadlec[a)]
Institute of Physics, Academy of Sciences of the Czech Republic, Na Slovance 2, 182 21 Prague 8, Czech Republic

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A compact and simple device suitable for performing experiments in reflection setup with ultrashort laser pulses with a continuously varying incidence angle is presented. As the incidence angle is varied, the direction of the input and output beams as well as the overall path length are conserved; only plane mirrors are used which avoids any wave-front distortion. The properties of the device are analyzed within geometrical optics. As a verification of the device functionality, we present experimental data for incidence angle dependent terahertz pulse generation obtained by optical rectification on a thin gold film. © *2005 American Institute of Physics.* [DOI: 10.1063/1.1868452]

I. INTRODUCTION

In the last decades, there has been a rapid development of laser sources generating ultrashort laser pulses. These pulses allow the scientists to study new phenomena, in particular in condensed matter, occurring on a time scale down to picoseconds or femtoseconds.[1,2] In these experiments, the properties of interest of the materials vary so rapidly that the signals cannot be resolved using oscilloscopes or other purely electronic devices. Therefore, as a rule, the laser pulses are split into two (or more) branches and a part of the beam power is used for detection via various nonlinear optoelectric or all-optical interactions (auto-or cross-correlation, up-conversion, photoswitching, and many more). The detection techniques require then the beam paths to be set up in a way to cross or overlap in a precise location. Another condition necessary to allow the detection is the coincidence of the pulses (pump and probe, or signal and sampling, etc.) in time. For this reason, the optical lengths of the beam branches have to be identical or very similar; the length difference, if present, leads to a time delay (pump-probe or similar) which is commonly changed as a measurement parameter by means of optical delay lines with retro-reflectors.

From the point of view of the samples, the experiments can be performed either in transmission or in reflection geometry. The latter is particularly important for optically thick (opaque) samples. Then, measurements can be performed in the reflection geometry in a configuration with a fixed incidence angle θ,[3–5] however, this approach may not be sufficient for the particular problem under study. In cases when θ has to be continuously varied, one possible solution is to build dedicated instruments where the optical path length is conserved as the sensing element itself is moved;[6] in other cases, it is possible to make use of optical fibers.[7] However, such solutions can be quite difficult to realize, and optical fibers are not convenient for all types of applications. Therefore, it appears desirable to dispose of a device which would allow one to continuously change, in one of the the beam branches, the angle of incidence on the sample under study while preserving the directions of both the input and output beam and of the optical path length.

One device of this kind was suggested by MacFarlane;[8] it makes use of two elliptical mirrors with the sample in their common focal point, and two turning mirrors in the other foci. The major advantage is the easy change of incidence angle—it is sufficient to rotate simultaneously the two turning mirrors. Thus, the device can be, in principle, built into a vacuum chamber in order to change θ without the need of breaking the vacuum. The main drawback is connected with the variable effective radius of curvature of the reflecting surface as θ is changed; consequently, the beam cross-section and divergence are functions of θ. To avoid this, it is possible to use the device in a self-imaging regime by focusing the input beam on the turning mirror; then, the spot size on the sample is independent of θ, however, θ is not well defined because there is a conical spread of the beam. Also note that a distortion of the originally plane wave-front may occur due to small misalignments and to the size of the beam in the focal point. Finally, from a technical point of view, the elliptical mirrors are not easy to build, possibly coat with a suitable metal and align.

Here we propose an alternative device which makes use of flat mirrors only; obviously, the asset is that the mirrors are easily available, and this approach removes completely all possible wave-front distortions. We analyze the properties of the device from the point of view of geometrical optics and discuss the possible ways of operation. Finally, in order to verify its usefulness, we present a set of experimental data obtained by measuring optical rectification of femtosecond pulses on thin gold films.

II. PRINCIPLE OF THE DEVICE

A. Description

In our device, the ray follows a path along the outline of a horizontal parallelogram which can be skewed within the

[a)]Electronic mail: kadlecf@fzu.cz

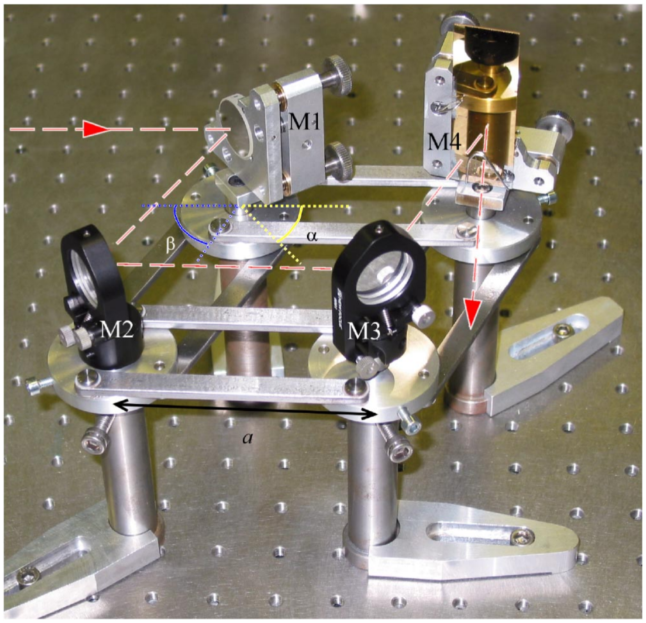

FIG. 1. (Color online). Overall view of the device mounted on the optical table. The dashed line indicates the path of the beam through the device. For explanation of symbols, see text.

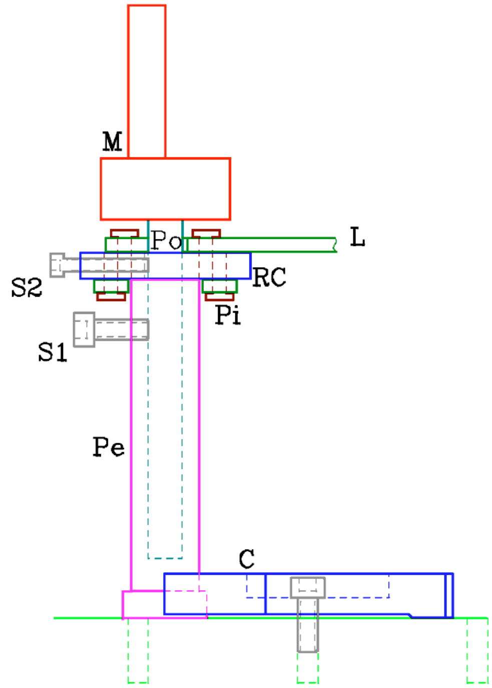

FIG. 2. (Color online). Main parts of the device. C—clamp for fixing to the optical table, Pe—pedestal, Po—post, RC—rotary collar, Pi—pivots, L—levers connected to the neighboring collars, M—mirror mount, S1, S2—fixing screws.

limits given by the size of the elements. An overall view of the device is shown in Fig. 1. The reflections occur in the four vertices, first on three flat mirrors M1-M3 and then on the flat sample surface which, for the purpose of analysis, can be considered as another mirror M4. A drawing showing the main parts in any one of the four corners is shown in Fig. 2.

Either of the mirrors or the sample is held in a mount M on post Po in such a way that the (vertical) axis of the post lies within the plane of the reflecting surface. The post can rotate inside the hollow pedestal Pe which can be fixed to the optical table by means of a clamp C. The post is encircled by a rotary collar RC containing four vertical pivots Pi at angles of 90° one from each other. Each collar is linked to the neighboring ones by means of straight levers L, all of the same length a, swiveling around the pivots. Fixing screws S1 and S2 allow to block the post within the pedestal and to fasten the collar to the post, respectively.

As seen from Fig. 1, the levers and collars make up together five parallelograms—the main one with the side length a, defining the beam path, and four smaller ones, each connecting a pair of adjacent collars. Thus, the function of the levers is twofold: (i) they maintain any two neighboring posts at the same distance a as the device is skewed and (ii) as long as the screws S2 are tightened, they ensure that if any of the posts is turned, the remaining ones rotate by the same angle. The device itself has two angular degrees in freedom which allow us to define, as shown in Fig. 1, two angles with respect to the plane defined by the axes of mirrors M1 and M4—the inclination angle α of the plane of the mirror M1 and the skew angle β of the plane connecting the axes of the mirrors M1 and M2.

B. Utilization

Before the use in the experiment, an initial alignment of the device has to be performed. To this purpose, it is convenient to work with beams parallel to the threaded holes of the optical table. First, one has to fix the posts for mirrors M1 and M4 to the optical table in a direction along one row of holes and to align, parallel to them, an adjustment laser beam. By setting the angle β to 90°, the main parallelogram becomes a square; the two other posts are attached to the table in this position. Then, it is necessary to adjust the four mirrors to the proper angles within the collars. First, the collars are turned in such a way that the four parallelograms become identical rectangles. With the aid of the laser beam, the mirror M1 is set to the angle $\alpha = 45°$; for a high precision, the straight portion of the beam path after reflection should be extended beyond the mirror M2 by removing it or flipping down. When this adjustment is finished, the screws S1 and S2 belonging to M1 are tightened. The same procedure is to be followed with the mirrors M2 and M3. The sample holder M4 can be either oriented in the same manner, or turned to a different arbitrary position as required by the direction of the output beam in the experiment (see Fig. 1). At the end, all the posts are held by means of S2 screws in the correct positions within the collars.

Once the initial alignment is done, the device can be moved to the experiment. While the S2 screws remain fastened, it is possible to release the S1 screws as necessary. The position of the posts for M4 (sample) and M1 has to be set appropriately, and these posts remain in place during the experiment. The choice of an appropriate incidence angle θ at M4 is performed in two steps. First, the S1 screws as well as the clamps for posts M2 and M3 are released; this enables one to set β by moving these two posts. After that, the posts are fixed in their new position and all four mirrors M1 to M4 are rotated simultaneously to an angle α such that the laser

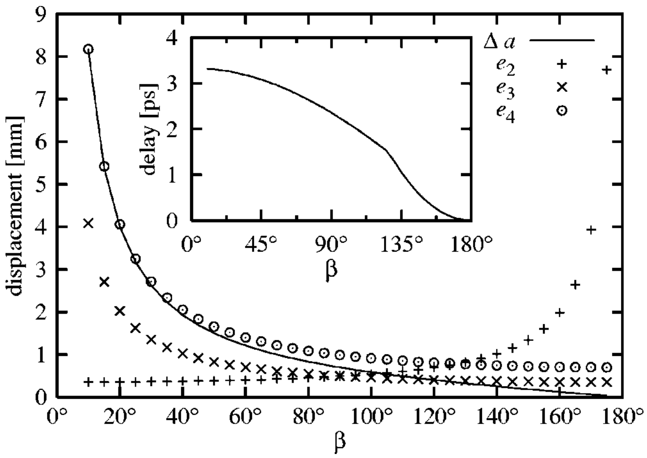

FIG. 3. Deviation of the path length Δa and of the offsets $e_2 - e_4$ depending on the angle β for $a = 100$ mm and a misalignment of α by 0.1°. Inset: absolute delay of an ultrashort pulse passing through the misaligned device where the highest of the values $e_2 - e_4$ is equal to 1 mm.

beam reflects off the mirrors at their centers. The change of θ is very simple and takes typically no more than a few minutes.

III. DISCUSSION

While the initial adjustment can be performed quite precisely, the change of θ is necessarily subject to imprecisions caused by geometrical factors. The angle β can be measured with a precision of ±1° with a protractor; in order to achieve a higher precision, it would be necessary to conceive a dedicated measurement tool. As mentioned above, the angles α and β represent two independent degrees of freedom of the device, however, for the beam to pass through the device in the proper way, any given value of β requires one to set the value $\alpha = (180° - \beta)/2$. The visual criterion for that is the position of the beam at the centers of individual mirrors. Given the geometrical properties of the device, an error in α has no influence on the value of θ; by contrast, such a misalignment will induce a change Δa in the overall path length $3a$ delimited by the intersections of the beam with M1 and M4.

In order to study theoretically the dependence Δa on the misalignment, we have set up a two-dimensional analytical model of the device using the principles of geometrical optics. We have employed the same value $a = 100$ mm as in the real device and supposed a beam incident exactly on the center of M1. The plane of the mirror M4 is oriented parallel with that of M3, i.e., the incoming and outgoing beams are ideally in the same line. The model enables us to trace the ray path for any pair of angles α, β; the quantities of interest are the deviation of the path length Δa from the ideal value and values e_2, e_3, e_4 of the horizontal offset of the beam trace with respect to the post axis at mirrors M2, M3, and M4, respectively. The results are summarized in Fig. 3 which shows the values of Δa, e_2, e_3, and e_4 as a function of β with a misalignment in α by 0.1°.

We see from Fig. 3 that for $\beta < 127°$, the misalignment manifests itself the most at the mirror M4; for $\beta > 127°$, the position of the spot on M2 is the most sensitive to α. The deviation Δa in our model situation is monotonically decreasing with β. For practical purposes, it is useful to consider a situation when α can be adjusted with a precision limited by the offsets e_2, e_3, e_4—either of them can attain some maximum value beyond which the misalignment can be seen by eye. The inset of Fig. 3 shows a curve calculated for a situation where the highest of the three offsets amounts to 1 mm; instead of Δa we plot the time delay corresponding to the propagation of an ultrashort light pulse over the distance Δa in free space. We see from here that the misalignment of the device in this typical situation does not exceed a few picoseconds within the whole range of β; this can be easily compensated by means of an optical delay line placed elsewhere in the same beam branch. This theoretical conclusion is confirmed by the experimental data, as we show below.

Finally, let us note that the setup imposes a limitation on the material of the mirrors—as the angles of incidence at individual mirrors vary in a broad range, metal-coated mirrors should be used while mirrors with stacks of dielectric layers, widely used in ultrafast techniques, are not convenient, as they are always designed for a narrow interval of incidence angles. This may be restricting for very intense ultrashort pulses where the fluence would exceed the damage threshold. Also, even for weak pulses, one has to bear in mind that a small part of the incident power is lost; this depends on the incidence angles at individual mirrors and on the beam polarization. Therefore, in real situations, the power incident on the sample will vary somewhat with θ which should be taken into account in the experiments, if relevant.

IV. EXPERIMENTAL RESULTS

We have employed the device shown in Fig. 1 to study the terahertz (THz) radiation due to optical rectification of ultrashort laser pulses at a metal surface; this method of generation of THz radiation has been discovered recently[9,10] and its principle is out of scope of the present article. The details of the experimental setup, as well as a discussion of the underlying mechanisms, are given in Refs. 10 and 11. Briefly, p-polarized pulses provided by a multipass Ti:sapphire amplifier with an energy of 0.7 mJ, a mean wavelength of $\lambda_0 = 810$ nm, and duration of $\Delta t = 50$ fs were directed to the present device and used to excite a 205 nm thick film of gold deposited on a glass substrate, under a varying angle of incidence. A [011] ZnTe crystal was employed as an electro-optic sensor for detection of the p-polarized component of the THz field. The electro-optic sampling requires the THz pulse to propagate through the nonlinear crystal collinearly with a sampling beam; therefore, the direction of propagation of the THz pulse has to be always constant, which is ideally ensured by the present device. The THz beam together with the device were placed in a low-pressure chamber in order to avoid absorption on water vapor. Between the individual measurements for different θ, the ambient pressure was restored and the device readjusted according to the procedure described above. Additionally, the position of the sample was slightly adjusted by means of the fine adjustment screws on

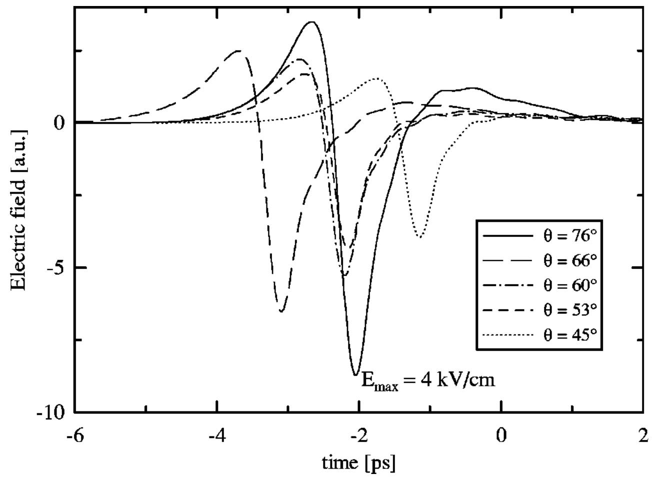

FIG. 4. Wave forms corresponding to pulses of THz radiation generated by optical rectification on a gold film with a thickness of 205 nm for different values of θ. The lines represent raw experimental data.

its holder, in order to obtain a maximum signal. The raw experimental data are shown in Fig. 4. We see that the change of θ did not shift the signal in time by more than a few picoseconds, in agreement with the analytical model. Also, the curve for θ=76° corresponds to a setup where the peak value of the electrical field of 4 kV/cm was achieved, which is to our knowledge the highest one obtained by means of optical rectification on a metal so far.

In summary, we have developed a device which, owing to the simplicity of its design and operation, is suitable for various applications in ultrafast measurement techniques in cases when it is useful to work in a reflective configuration with a varying incidence angle θ. As a prominent feature, the orientation of the input and output beams as well as the optical path length are independent of θ which meets the needs of various ultrafast detection techniques.

ACKNOWLEDGMENT

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