Polarization Assessment and Monitoring of Infrared Beams

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Beam propagation as well as beam interaction are generally not independent of the polarization state. Therefore a laser beam´s characterization can not be complete without a polarization analysis. This contribution describes our development of specialized instrumentation for polarimetry of infrared laser beams in the power range from 10 mW to 3 kW.

Introduction

Most surfaces of an optical component or of a laser beam's target are isotropic in respect to polarization. In other words, the polarization state plays no role in the optical effect as long as the incidence is normal to the surface. Any non-normal incidence however breaks the symmetry and results in polarization-dependent reflection and absorption. This is well known from Fresnel's equations for dielectric or conductive surfaces.

Special care is necessary when a beam transport sytem has to deliver a well-defined polarization. As an example, consider the several 90° reflections occurring in the beam guide of a laser cutting robot. To preserve the mostly desired circular polarization special reflectors have to be employed ("zero-phase-mirrors"). The certification of the desired phase tolerance of such components as well as the control of the critical adjustments of incidence and azimuth angles makes the development of polarization-measuring devices necessary.

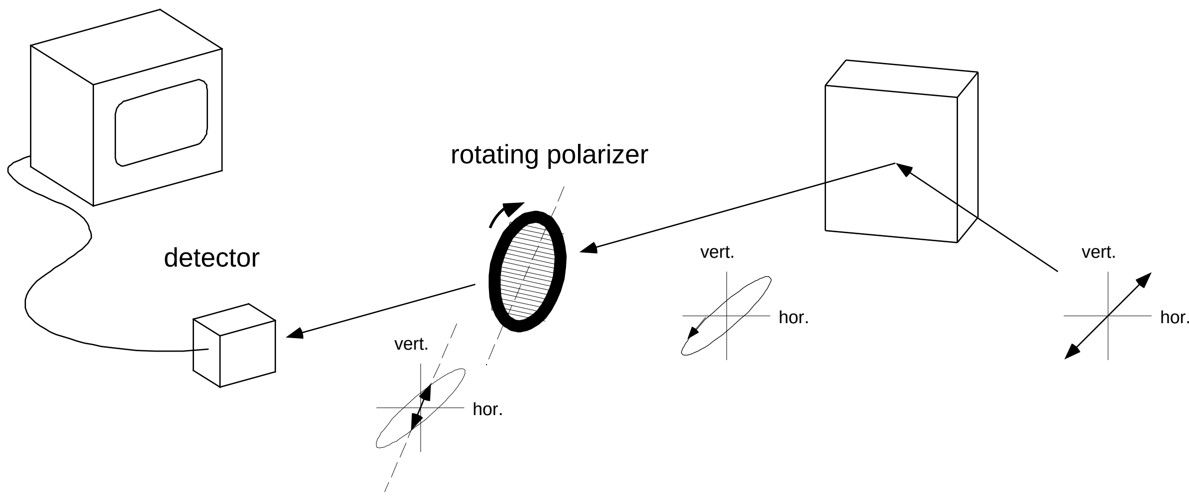
At the beginning of the laser machining era, however, it was not clear that the polarization would be a relevant beam characteristic at all; typically the laser beam was applied *normally* to the target for drilling or cutting. It then came as a surprise that in specific applications as for example the cutting of sheet metal with high-power CO_2 lasers a strong polarization effect was indeed found. This polarization sensitivity directly leads to unwanted polarization-dependent results.

Two strategies have been demonstrated which allow to achieve an isotropic processing quality: (i) the use of linear polarization with active steering of the orientation such that the electric field remains parallel to the momentary cutting direction, and (ii) the use of circular polarization.

Both solutions clearly demand specialized instrumentation to monitor the beam's polarization state and to adjust it to the desired one. This contribution highlights the situation with infrared polarization measurements.

Polarimeter

The art of polarization measurement has evolved into one of the most precise optical measurement techniques. Especially in the configuration of ellipsometry a very high resolution capable of characterizing nanometric thin films has been achieved, with applications ranging from pharmacy to semiconductor processing. The basic setup can directly be used to perform the measurements required for laser beam characterization. The principle of measurement is shown in the following sketch.



Rotating-analyzer polarimetry/ellipsometry

A beam with known polarization state (usually linear, oriented at 45^o azimuth angle in respect to the incidence plane) is reflected at the sample under test. The output polarization is in general no longer linear but has acquired some ellipticity, given by both a phase difference δ and an amplitude ratio for the in-plane vs. the out-of-plane electric field components. The task is then to precisely determine the polarization ellipse in an instrument called polarimeter.

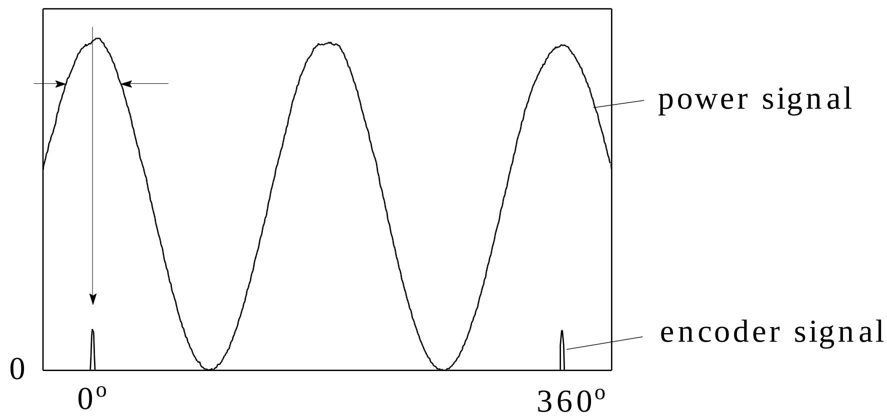
The basic polarimeter design uses a rotating linear polarizer as shown above. In this the polarizer transmits beam power which varies according to the projection of the polarizer's direction onto the ellipse to be measured. A power detector then records a sinusoidally varying signal P(t), modulated at 2f where f is the rotation frequency. The shape of the ellipse is fully determined by measuring the minimum and maximum power signals, to obtain the "circularity" ratio $r = P_{min}/P_{max}$. The circularity ratio is zero for linear and 1 for circular polarization.

The orientation of the ellipse completes the measurement. This is usually given by the angle α at which the maximum signal occurs. For this measurement it is necessary to refer the time of maximum signal to an angular encoder signal coming from the rotating polarizer.

Measurement examples

We illustrate the determination of the polarization ellipse by the following measured recordings.

A.

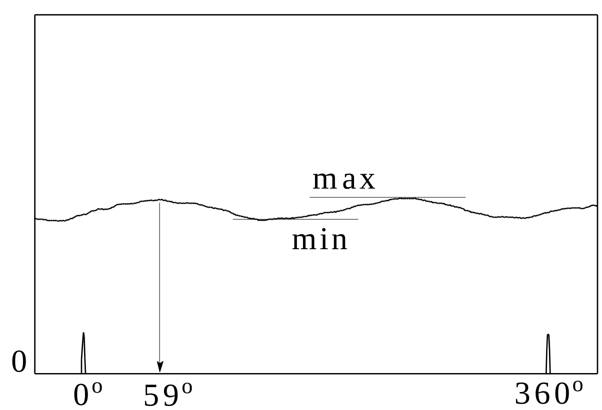


Linear polarization

This trace measures a linearly polarized laser beam since the power goes down to zero, at the times of cross orientation of the polarizer. As the time of maximum power signal coincides with the occurrence of an encoder signal peak, the orientation of the laser polarization electric field is known to coincide with the polarimeter's orientation, usually horizontal.

A situation typical for the machining application of a CO_2 laser beam is shown in the next example.

B.



Near-circular polarization

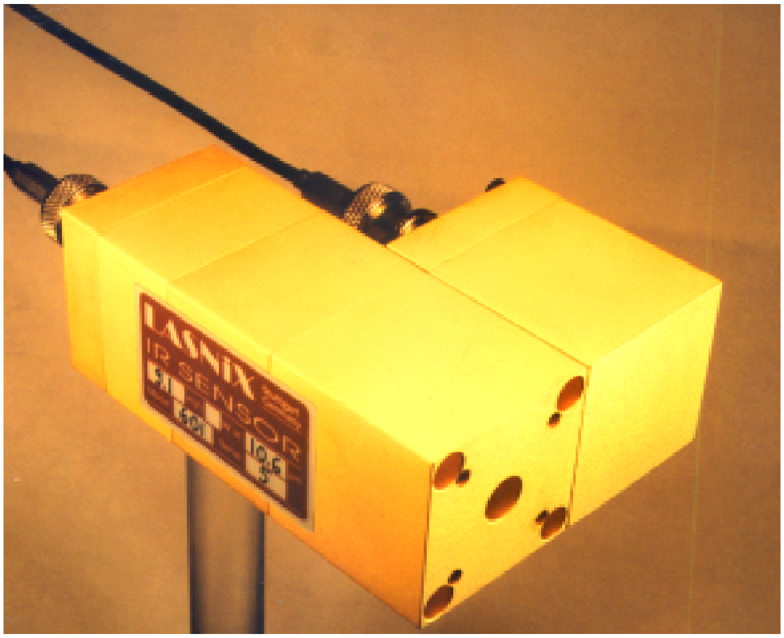
Ideally the polarization should be circular but we observe that the power signal is not constant, appearing slightly modulated with a circularity ratio $r = P_{min}/P_{max} \approx 0.88$. The maximum power signal is seen to occur at an angular position of $\alpha \approx 59^{o}$ from the encoder peak, i.e. from the horizontal in anticlockwise direction as viewed from the laser. Both informations, r and α, together determine the ellipse. Furthermore, they uniquely prescribe how to readjust the retarder to obtain perfect circularity. As seen from the polarization tuning graph below, it is necessary to decrease the azimuth angle by 0.8^{o}, as well as to increase the phase shift by 3.2^{o}.

Infrared polarization sensors

The basic design question for a polarimeter is to decide on a suitable polarizer. In the visible polarizers are based on reflection from flat glass surfaces, for example, or on double refraction. In the infrared one can similarly use coated or uncoated flats for a reflection-type polarizer. However, the infrared has the additional choice of using the metal wire grid invented by Hertz a century ago. Such grid polarizers e.g. on ZnSe substrate have the advantage of a very compact transmitting device. The suppression of unwanted polarization has however been a problem with these components.

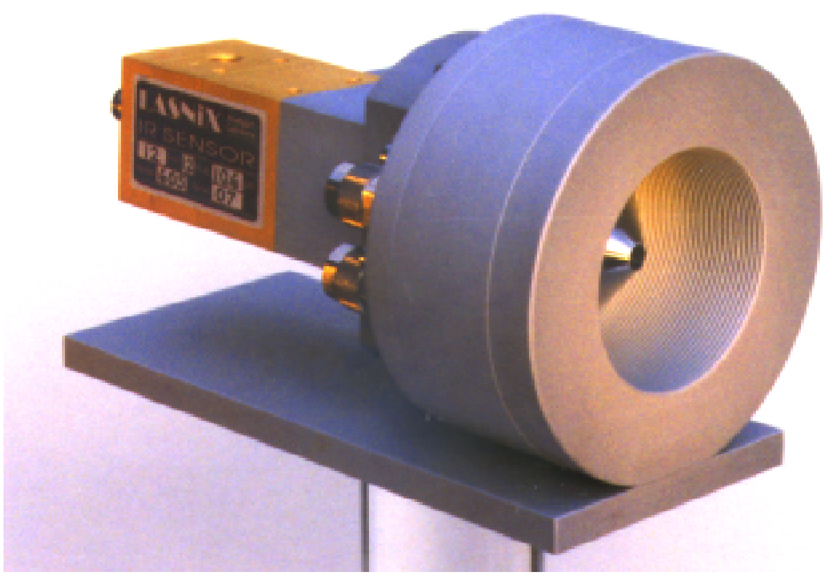
For ellipsometry one needs indeed a possibly high polarization contrast. Consequently we have improved the design of the wire grid polarizer by optimizing the wire cross section (U.S. patent # 5,177,635, 1993). As a result, infrared polarizers with contrast ratio exceeding 10000:1 are now available as a standard component (LASNIX LP series).

LASNIX polarization sensors are equipped with such a high-contrast rotating polarizer. Specifically our aim was to develop simple and portable instruments with no compromise in accuracy. This necessitated the development of a power detector with reliably non-polarization-dependent responsivity. The compact polarization sensors mods. 601 and 605 determine the polarization status of a CO_2 laser beam precisely and rapidly. They contain a battery-powered motor the fast d.c.-to-100 Hz power sensor, and an angular encoder which generates angular position signals. A measurement cycle takes 1 s.



Polarization sensor Mod. 601

The basic device Mod. 601 is only 9 cm in the length and weighs 350 g. It can take up to 30 W c.w. into the 4 mm input aperture. A minimal power of about 100 mW is recommended to determine the polarization with high accuracy.

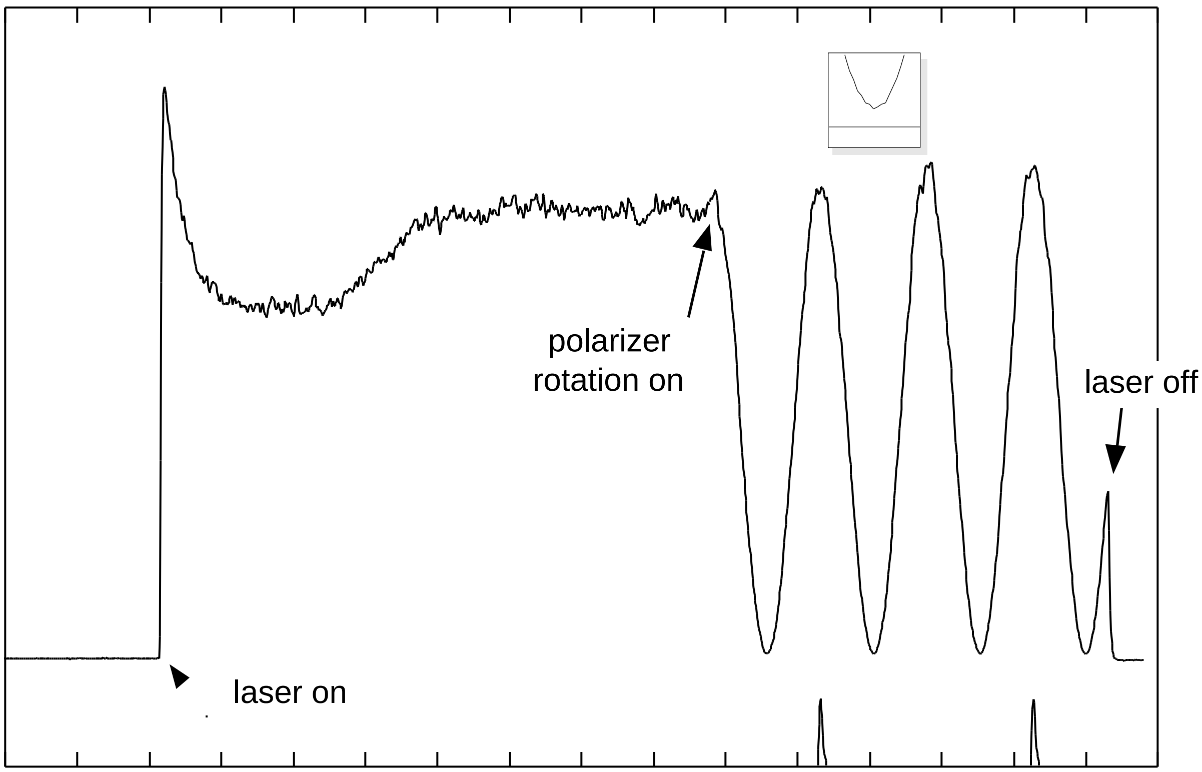


Polarization sensor Mod. 605

For diagnosing high-power industrial laser beams a beam sampler complements the basic device. The sensor Mod. 605 comprises a beam dump cooled by water to handle up to 3 kW beams in its 5 cm diameter aperture. Inside the sampler is a non-polarizing x10 diffractive attenuator, proprietary to LASNIX.

Testing kilowatt laser output

The linearity of an industrial high-power CO_2 laser's output polarization can be tested by simply inserting the mod. 605 sensor into the high-power beam path. The common procedure is to connect both sensor output coaxial cables to a small oscilloscope such as the battery-operated Iwatsu 8600.



Mod. 605 response to multi-kW CO_2 laser beam

The output traces were recorded during a 15 s observation period with a Trumpf TLF5000 Turbo CO_2 laser. At the beginning the motor was off, so that the power signal faithfully recorded the start-up behaviour of the laser. When the laser had stabilized, the motor was started. Just before the completion of two turns the laser was switched off. Clearly the polarization is nearly linear, but not quite, since the power minimum is slightly above zero (see x10 expanded inset).

Circularity tuning of 3 kW CO_2 laser beam

The recorded trace of the above example B was in fact recorded with a Mod. 605 sensor in a 3 kW beam. To interpret the measured quantities it is helpful to resort to a retarder tuning graph which is supplied with the instrument. Here we give its derivation following the analysis in text books such as Born & Wolf, *Principles of Optics*. In short, it is assumed that the laser beam has a horizontal and a vertical field component, E_h and E_v respectively, with relative phase difference δ, so that

$$E = E_h \cos(\omega t) + E_v \cos(\omega t+\delta). \qquad (1)$$

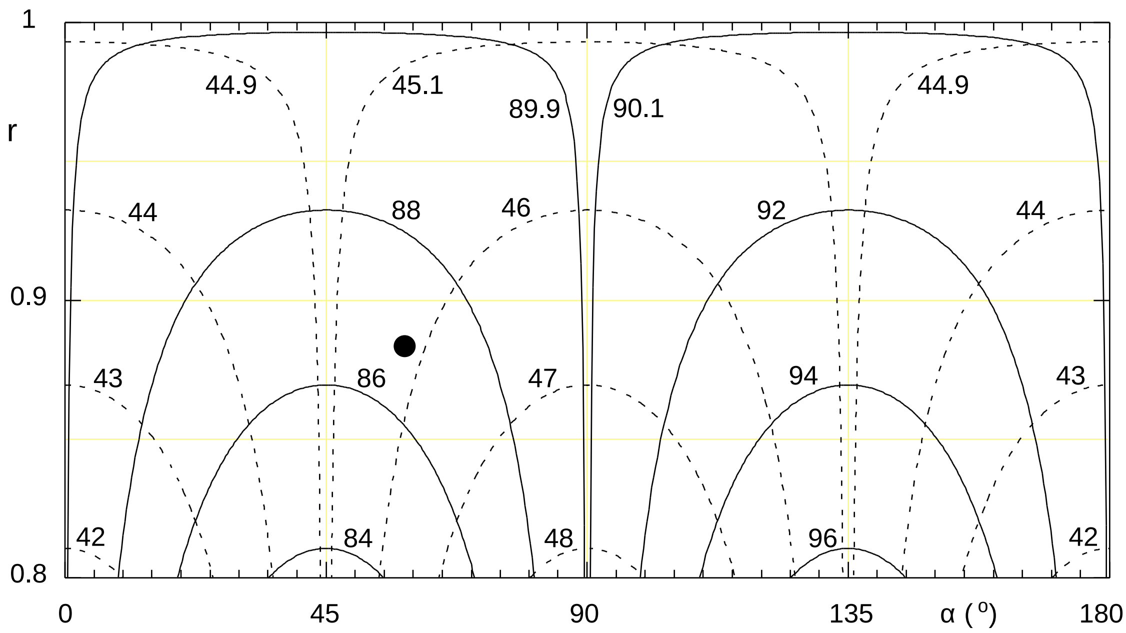
The field E can be shown to describe an ellipse. With the definition of an azimuth angle $\alpha_0 = \arctan(E_v/E_h)$ the ellipse has an axial ratio ρ and its maior axis is oriented at an angle α where

$$\rho = \tan(0.5 \arcsin(\sin(2\alpha_0) \sin\delta)), \qquad (2)$$
$$\alpha = 0.5 \arctan(\tan(2\alpha_0) \cos\delta). \qquad (3)$$

When this beam is transmitted through a linear polarizer as in the mod. 605 polarization sensor the measured power ratio is $r = P_{min}/P_{max} = \rho^2$ and the power maximum occurs at a polarizer orientation α. According to eqs. 2 & 3 it is possible to determine both quantities α_0 and δ from a measurement of r and α.

The following retarder tuning chart makes this determination very easy, because it allows a direct reading of the values and thus avoids to work with eqs. 2 & 3. The graph itself is made by using eqs. 2 & 3 to plot r *vs* α, and obtain two families of curves, one with α_0 = const. (broken), the other with δ = const (full). Since any measurement with the polarization sensor results in a distinct pair of values r,α this defines a single point in the tuning graph. This point in turn uniquely determines one pair of α_0,δ values characterizing the retarder alignment.

Coming back to the measured recording of the above example B, the result is marked as a black dot in the tuning graph. From this graph it then becomes clear that $\alpha_0 \approx 45.8^o$, $\delta \approx 86.8^o$. Consequently, in order to achieve perfect circularity (r=1), *two* separate adjustments have now to be carried out: the retarder has to be rotated by 0.8^o clockwise around the optic axis, so that $\alpha_0 = 45^o$, and secondly, the phase shift of the retarder has to be increased by 3.2^o so that $\delta = 90^o$.



Retarder tuning graph

Summary

Our development has resulted in compact, accurate polarization sensors for infrared laser beams. Applications with high-power industrial beams are the testing and the adjustment for either ideal linearity or circularity of the polarization. Further applications are in component testing and in general infrared ellipsometry.