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# Real-time control of polarization in ultra-short pulse laser micro-processing

O. J. Allegre[1], W. Perrie[1], K. Bauchert[2], D. Liu[1], S. P. Edwardson[1], G. Dearden[1] and K. G. Watkins[1]
[1] Laser Group, Department of Engineering, University of Liverpool, Liverpool, L69 3GQ, UK
[2] Boulder Nonlinear Systems, Inc., Lafayette CO 80026, USA

**Abstract.** The use of a fast-response, transmissive, ferroelectric liquid-crystal device for real-time control of the polarization direction of a femtosecond laser beam, and the benefits on various aspects of ultra-short pulse micro-processing, are discussed. Several configurations have been used for driving the polarization in real-time. Following successful testing of these applications, real-time polarization control has emerged as a flexible toolbox for the laser processing engineer. Microscopic investigation of the produced features revealed the significant improvement in process quality.

**Keywords:** Ultra-short pulse laser, Polarization, Micro-drilling.

## 1 Introduction

The past decade has seen the development of ultra-short pulse lasers, with processes based on femtosecond and picosecond pulse durations becoming increasingly widespread. Thanks to the ultra-short timescale on which laser energy is coupled to the material, high precision sub-micron machining of metals has been achieved with very little thermal damage [1], [2]. Industrial applications include the very precise drilling of holes for fuel-injection nozzles in the automotive industry [2], [3]. The key parameters influencing the laser-machining process quality are the pulse duration, wavelength, peak power, beam quality and polarization [4]-[6].

The influence of polarization on micro-machining has been experimentally demonstrated in [6]-[10], showing that drilling high-aspect-ratio (depth/diameter) microscopic holes in metal with linear polarized ultra-short-pulse lasers produces anisotropic profiles. This is due to the higher reflectivity of the *s*-polarized radiation, relative to the *p*-polarized radiation [7]. As the hole develops through the material, the *p*-polarized radiation is more readily absorbed in the sidewalls, whereas the *s*-polarized radiation tends to be reflected down to the base of the hole. This results in a distorted hole when the beam reaches the exit side. The simplest way to reduce these distortions is to use a circular polarized beam, which removes the differential in reflectivity during drilling. In some cases however, the remaining distortions associated with circular polarization are not satisfactory [6]. Another technique, referred to as *polarization trepanning*, consists of rotating the linear polarization during drilling to further improve the hole quality [7], [10]. The trepanning optic developed in [8] produced holes of remarkable quality using this technique. However, these methods involve mechanical rotation of optical components and could be adversely affected by vibrations and prone to mechanical failure, leading to potentially expensive maintenance. An alternative laser-specific polarization switching method is detailed in [5]. It is based on an intra-cavity polarization chopper wheel synchronized to the laser pulse train. However, this method requires the laser cavity to be re-designed and therefore cannot be easily applied to existing laser systems.

In this paper, we propose a flexible method for rapidly switching the linear polarization of a laser beam between two orthogonal directions during micro-machining, using a fast-response liquid-crystal polarization rotator. As a proof of principle, helical drilling tests were performed on stainless steel using various polarization configurations. The early experimental results using a femtosecond laser system show a small, but consistent improvement of the micro-drilling quality compared to linear or circular polarization configurations.

## 2 Experiment

### 2.1 Experimental setup

The experimental setup is shown in Fig. 1. The output from a femtosecond laser system (Clarke-MXR CPA2010, with a minimum pulse width of 160fs, 775nm central wavelength, 1mJ maximum pulse energy, 1kHz repetition rate and vertical linear polarization) is attenuated by a half-wave-plate and a glan laser polarizer. The resulting horizontally polarized beam is incident on a transmissive, ferroelectric, liquid-crystal polarization rotator developed by Boulder Nonlinear Systems, Inc.

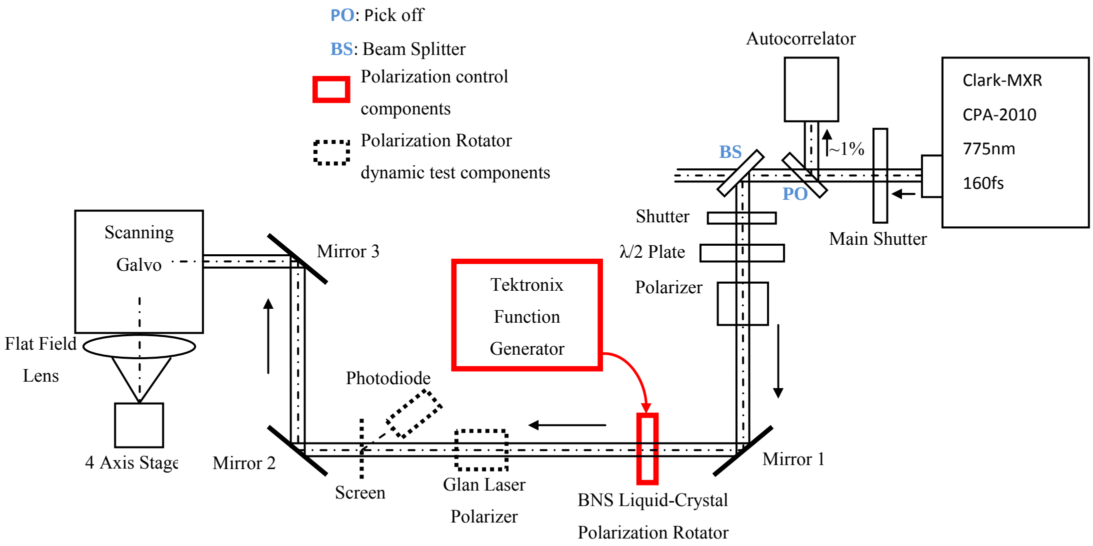



**Fig. 1.** Helical drilling experimental setup showing how the liquid-crystal polarization rotator was used. For the drilling tests, the dashed components were removed. This setup is a modified version of the one used in [11].

(MS Series). The liquid-crystal polarization rotator offers a switching speed of up to 20kHz between two orthogonal output states, with a response time of typically less than 100µs. This device behaves like a zero-order half-wave retarder mounted in a mechanical rotation stage. Varying the electric field applied to the device is equivalent to rotating the mechanical stage. The polarization rotator is driven by a programmable waveform from a function generator (Tektronix). After reflection on Mirrors 2 and 3, the beam enters the 10mm aperture of a scanning galvo system with a flat field lens (f = 100mm), driven by a programmable PC interface board. Samples are mounted on a precision 4-axis (x, y, z, θ) motion control system (Aerotech) allowing accurate positioning of the sample at the laser focus.

### 2.2 Test strategy

In helical drilling, the laser beam performs a circular movement with a defined diameter on the surface of the work piece. As material is removed by each pulse, the beam works its way through the material on a helical path. The parameters influencing the geometry of the machined hole include the diameter of the circular beam path, the ablation spot size and the polarization [6].

Series of helical drilling tests were performed on 380µm thick stainless steel samples. Circular beam paths with diameters of 55, 65 and 70µm were programmed on the scanning galvo. A pulse energy value of 75µJ was used, corresponding to a fluence of 20J/cm$^2$. This produced ablation spot diameters of typically around 60µm. As the fluence was much higher than the ablation threshold (around 0.1J/cm$^2$ for steel), some melting occurred at the entrance of the holes, but the overall drilling time per hole was reduced to below 60s. The test strategy consisted of using the various polarization modes available with the liquid-crystal polarization rotator, varying the operating parameters to improve the circularity and reduce the taper of the micro-holes. Linear and circular polarized beams were used first to provide comparative data for subsequent tests. The experimental configuration of the setup for each test is summarized in Table 1.

## 3 Results and discussion

The helical drilling tests produced tapered holes with an entrance opening diameter of typically around 110µm corresponding to a programmed circular beam path of 65µm in diameter and a pulse energy of 75µJ. The entrance of the holes showed no dependence on polarization, but was slightly elliptical in shape due to the ellipticity of the incident laser beam profile. On the exit side, the shape and taper of the holes varied with polarization, with a typical half-angle side-wall taper ranging between 4º and 5º. A summary of the test results as well as SEM images of the exit holes for the various polarization modes are shown in Table 1.

### 3.1 Scanner-synchronized polarization switching

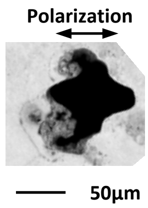
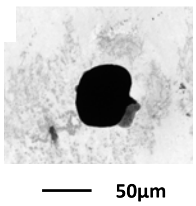
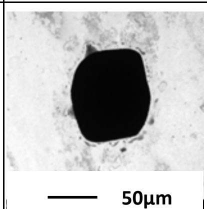
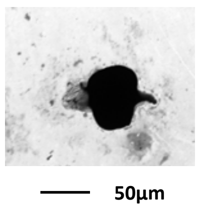
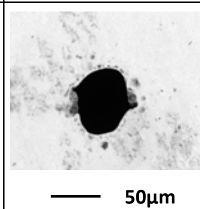
In *polarization trepanning*, the direction of linear polarization rotates synchronously to the beam motion around the hole so that it is always oriented in the same way with regard to the wall [6]. This is normally achieved by placing a wave-plate in the optical path and mechanically rotating it synchronously with the beam. In order to obtain a similar effect, our liquid-crystal polarization rotator was synchronized with the scanning galvo head. As only two orthogonal directions of polarization were available, this test produced an approximation of *polarization trepanning* by maintaining the direction of polarization as close as possible to a *p*-polarization during helical drilling. Our experimental results are described in Table 1. The quality of holes drilled using this method was limited by only having two directions of polarization. However, optical *polarization trepanning* in this way may prove useful when drilling geometric shapes, such as square- and cross-shaped holes or cutting linear grooves, where the polarization direction can be best optimized.

### 3.2 Laser-synchronized polarization switching

In this mode, the polarization rotator was synchronized with the kHz femtosecond-pulse-train from the laser. Our helical drilling tests showed reduced distortions in the shape of the exit holes compared to linear polarization (see Table 1). This was due to the averaging of reflectivity during drilling. This averaging effect occured because the polarization rotator was not synchronized with the scanning galvo in this case. The averaging effect is discussed further in section 3.3.

We also used the laser-synchronized polarization switching mode to test the response time of the liquid-crystal device, by placing a Glan Laser Polarizer behind it. Thus, a rotation in polarization direction was translated into a modulation of the amplitude transmitted through the polarizer. The resulting beam amplitude was measured with a photodiode (see dashed components in Fig. 1). This confirmed that the response time of the polarization rotator was less than 0.5ms (manufacturing specification: 0.1ms). In our laser system, the time lapse

**Table 1.** Description and results of helical drilling tests on a 380µm-thick stainless steel plate, including qualitative comparison of the exit holes (775nm, 240fs pulses, 1kHz repetition rate, pulse energy: 75µJ).

| | **Linear polarization** | **Circular polarization** | **Scanner-synchronized polarization switching** | **Laser-synchronized polarization switching** | **Un-synchronized polarization switching** |
|---|---|---|---|---|---|
| **Configuration of the setup** | Polarization rotator removed. The linear polarized laser beam is used to drill the sample. | Polarization rotator removed. A quarter-wave plate is inserted into the beam path to produce circular polarization. | Polarization rotator driven with a 10Hz square wave synchronized with the galvo scanner. | Polarization rotator driven with a 100Hz square wave synchronized with the laser pulse-train. | Polarization rotator driven with a 10Hz square wave, not synchronized with the laser or the galvo scanner. |
| **Aim of test** | Provide comparative data for subsequent tests. | Provide comparative data for subsequent tests. | Reduce the variability in reflectivity during drilling. This configuration is similar to polarization trepanning. | Provide accurate control of the polarization state of each femtosecond pulse. | Reduce the polarization induced distortions thanks to averaging effects. |
| **SEM images of the holes exit aperture** |   |   |   |   |   |
| **Qualitative comparison** | Elliptical exit hole shape, showing the distortions typically associated with linear polarization, as described in [7]. | Exit hole less elliptical than linear polarization. Low levels of distortion on the hole walls. | Increase in size of exit aperture compared to other polarization configurations. Small levels of distortion on the hole walls are still present. | Shape of the hole improved compared to linear polarization. No improvements when compared to circular polarization. | Increase in size of exit aperture compared to circular polarization. Low levels of distortion on the hole walls. |

between each femtosecond pulse is 1ms (1kHz repetition rate). The response time of the liquid-crystal device was therefore sufficient to provide accurate control over the polarization direction of each individual pulse. The interesting aspect of this polarization mode is that it enables dynamic pulse-to-pulse amplitude control for surface machining of periodic structures. Experiments using this technique (in preparation) will be published elsewhere.

### 3.3 Un-synchronized polarization switching

During helical drilling, the laser beam rotates about the central axis of the hole. When the polarization rotator is not synchronized with the scanner system, a given coordinate in the circular beam path will see the polarization direction vary over time. The resulting value for the reflectivity of the laser beam at this coordinate will vary accordingly. This leads to an averaging effect which tends to reduce the distortions in the exit shape of the hole [7].

The synchronizing signals linked to the polarization rotator were removed, allowing these averaging effects to take place. Our helical drilling tests showed reduced distortions in the shape of the exit holes compared to the other polarization modes (see Table 1). However, these averaging effects should also have occurred in the laser-synchronized polarization mode described in section 3.2. The difference in machining quality between these two cases is thought to be due to a difference in the polarization switching frequencies. Future work will determine the optimum ratio between polarization switching frequency and beam scanning speed to maximize the averaging effects and improve the machining quality.

## 4 Conclusions

A method for dynamically switching the polarization direction of a femtosecond laser beam with a fast-response, transmissive, ferroelectric liquid-crystal device has been presented. Helical drilling of high-aspect-ratio micro-holes in a steel plate was tested, using the various polarization driving modes available, such as scanner-synchronized, laser-synchronized and un-synchronized polarization switching. Microscopic investigation of the resulting features revealed improvements in the machining quality. A profitable line of future experimental work could be testing different geometries, aspect-ratios and materials to confirm these preliminary findings.

To our knowledge, this is the first time *polarization trepanning* has been achieved using a solid-state device for micro-machining. The liquid-crystal polarization rotator is found to provide more flexibility than the wave-plate elements it replaces, thanks to its tolerance to optical miss-alignment. Since it is a solid-state device, it provides polarization rotation without any undesirable mechanical motion, associated vibrational problems and reducing maintenance downtime. However, the liquid-crystal device is not without some operational constraints. For example its angular rotation range, limited to 90º and its requirement for a dc-balanced, 50% duty-cycle periodic driving voltage. As a result, the device is limited to machining periodic structures, or axi-symmetric features.

Although the machining quality often associated with high-precision trepan drilling heads has not been achieved, the fast-response liquid-crystal polarization rotator presented here could emerge as a flexible alternative, providing an improved machining quality to existing micro-machining systems.

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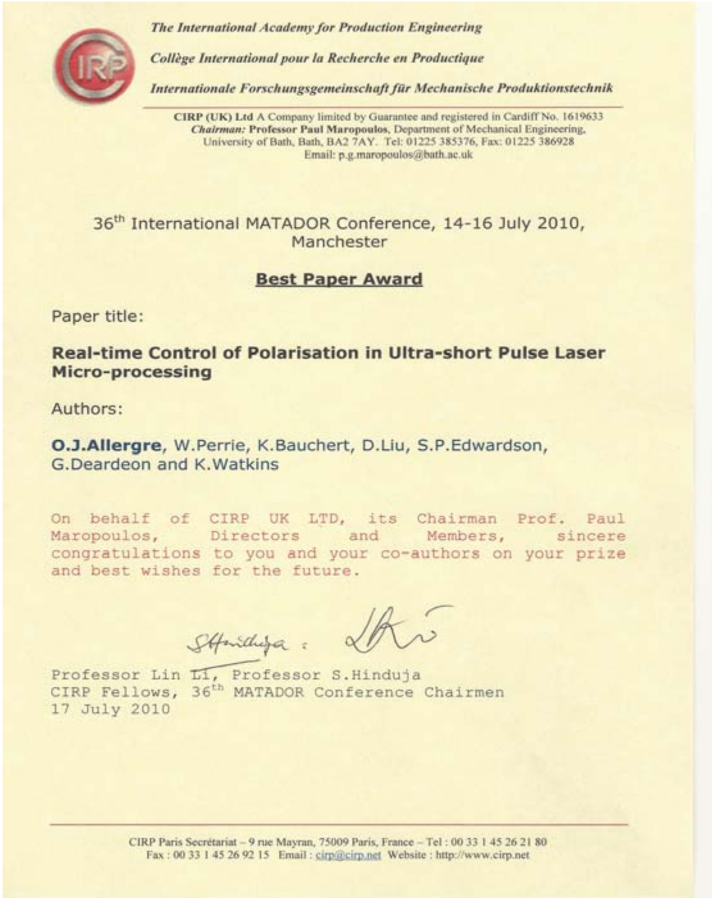

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Email: p.g.maropoulos@bath.ac.uk

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