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Telecentric CO_2 laser ring-cutting system with adjustable diameter

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Abstract

This contribution presents an optical setup for the generation of a telecentric ring focus with an adjustable diameter for cutting applications. The system is designed for the use of a CO_2 laser at 10.6 µm working wavelength and is adapted to an observation microscope for examining and selecting the sample at first. Subsequently, it cuts a small circular region with a single shot. The main application is the cutting of thin polymer films such as forensic adhesive tapes for trace selection. The diameter of the ring can be continuously tuned between 500 µm and 2 mm where a kerf of less than 20 µm is realized. To compensate potential height differences of the samples, telecentricity in the target plane for all adjustable ring diameters is demanded. Therefor the aperture stop of the focussing lens has to be filled with a variable angular spectrum. Variable ring diameter and the compliance of the telecentricity condition have been achieved by a modular optical setup which includes three axicon elements as key components. An axial shift of one of these axicons results in a varying angular spectrum in the aperture stop and therefore, the required specifications in the target plane are fulfilled. The optical design principle which creates the telecentric and size-variable ring focus will be discussed at first. Secondly, the adaption of the ring-cutting system to the observation microscope will be presented. Observation focus and ring cutting profile are aligned in the target plane and are coupled dynamically to allow a combined movement e.g. for focus variation. Subsequently, the properties of the realized system will be demonstrated by reference to cutting experiments on different polymer tapes. Finally, further cutting examples, for instance from the field of biotechnology, will be shown.

Keywords: micro-cutting of polymer films; axicon; annular laser profile; telecentricity;

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1. Introduction

While for most laser applications a Gaussian or top-hat profile is used, numerous applications require a ring-shaped intensity distribution in the target plane. These applications include optical tweezers [Shao et al., 2007], the illumination systems for projection lithography [Herkommer, 2010] and laser micromachining [Zeng et al., 2006; Klimowych, 2014]. To generate the ring-shaped intensity distribution conical axicons as the key optical elements are frequently used [Dickey, 2014]. The combination of a single axicon lens with a focusing element creates a focused ring at the focal plane of the setup with a fixed ring diameter. If a variable ring diameter is desired, typically at least two axicons are necessary. The corresponding systems combine either positive and negative axicons [Rioux et al., 1978] or, most prevalent due to difficulties in manufacturing of concave axicons, two positive axicons with additional refractive lenses [Dickey et al., 2011]. With increasing demands these simple approaches have to be extended to fulfill further specifications.

This contribution presents a setup for the generation of a telecentric ring focus with an adjustable diameter for cutting applications. The system is designed for the use of a CO_2 laser at 10.6 µm working wavelength and is adapted to an observation microscope. The main application of this system is the extraction of small circular sections from polymer films like forensic adhesive tapes. The observation microscope is used to select specific sample details (e.g., skin particles) on the adhesive tape, which are cut out and analyzed in further steps.

[Shao et al., 2006] developed a variable diameter ring-cutting system for an extremely different wavelength (1070 nm), which is used as a starting point. Due to forensic sample details a significant axial height deviation of the polymer tape position from the focal plane might occur. To increase flexibility in the target plane while simultaneously keeping process conditions constant, the ring diameter has to be constant over an extended axial depth. Therefor telecentricity in the target area was demanded for the variable diameter ring-cutting system. Further challenges are associated with the combination and adjustment of the cutting system with the observation microscope. Due to the different working wavelengths of the cutting system and the microscope, a combined beam path using the microscope objective for both functions is not possible. However, for the combined setup the axial and lateral position of the ring focus has to match the selected sample detail. This demand has to be fulfilled even when the object height has to be adjusted (e.g. change of sample holder). In particular, the ring-cutting system has to follow the movement of the observing microscope objective simultaneously when the axial height is adjusted.

2. Working principle and optical design of telecentric ring-cutting system

The overall system addresses as the main application forensic investigations where zoom microscopes are common tools in a broad range of disciplines [De Forest et al, 2001; Robertson, 2009]. Hence, a zoom microscope (Zeiss Axio Zoom.V16) forms the base of the overall system and the CO_2 laser cutting unit has to be adapted to the body and mechanical concept of the microscope. The typical operational procedure comprises two subsequent steps. In a first step the target (e.g. skin particle on a polymer adhesive tape) is selected with the aid of the zoom microscope after which a ring-shaped region including the target is extracted using the CO_2 laser cutting unit. The optical paths for both tasks have to be aligned to each other to make sure that the selected sample is cut out properly. As mentioned above it is not possible to combine the beam paths due to the different working wavelengths. For this reason separated, but aligned and adapted beam paths are necessary.

2.1. System Overview

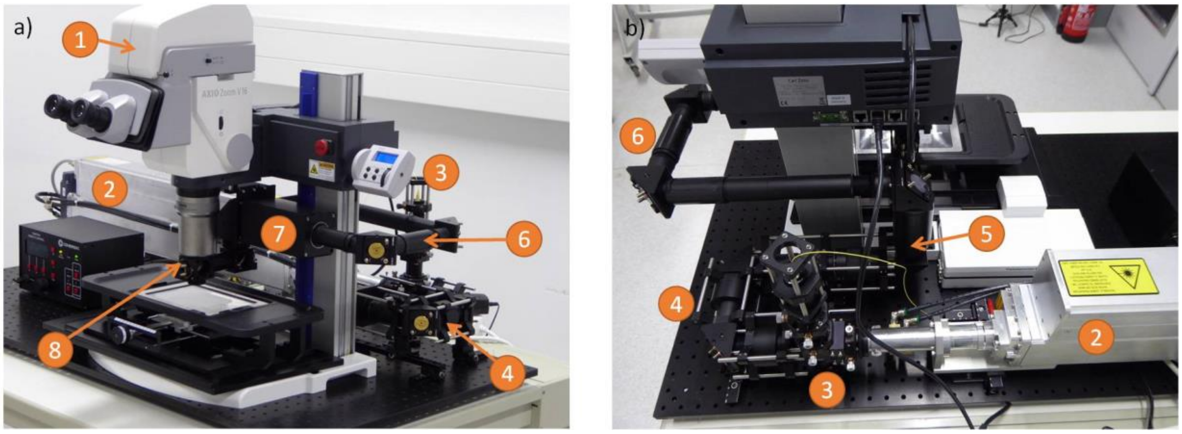

Fig. 1. Photographs of the overall system combining an observation microscope, a CO_2 laser source and the optical setup for the ring-cutting system with adjustable diameter; Diagonal view of the front side (a) and a backside view (b) of the ring-cutting system. Different subassemblies are labeled with numbers: observation microscope (1), CO_2 laser (2), couple unit for pilot laser (3), beam expander (4), optical staircase (5), ring-shaping unit (6), axicon telescope pair (7) and final focusing group (8).

Photographs showing the overall system (see Figure 1a) and 1b)), in particular the microscope (white), the CO_2 laser source (Coherent, Diamond E-150) (silver-coloured) and the optical modules of the CO_2 cutting system (black). The individual subassemblies are labeled with coloured numbers. All the subassemblies are mounted on the base plate, the main profile column or the body of the microscope. The cutting system allows sufficient adjustment capabilities and is very compact at the same time. For alignment purposes, a pilot laser at 650 nm is combined with the 10.6 µm beam path using a beam splitter (labeled 3 in Figure 1b). The pilot laser does not form a ring focus in the target plane due to significant different refractive indices for 10.6 µm and 650 nm, but it allows the centering of the optical components on the optical axis. The laser light propagates through a beam expander (4), a first ring-shaping group (6), an axicon telescope pair (7), and a final focusing group (8). An optical staircase (5) is necessary, because the CO_2 laser is fixed on the base plate while the final focusing group has to follow the microscope movement in case of height adjustments.

The final focusing group is mounted in a horizontal pivoting arm, which can be moved under the microscope objective to switch from microscope procedure to cutting operation. Hereby, the setup benefits from the large working distance of the microscope objective (55 mm). A magnetic contact allows a reproducible alignment of the infrared optical unit.

2.2. Optical Design

The specifications of the optical setup are derived from the application demands. For laser cutting applications of polymer tapes the CO_2 laser at a working wavelength of 10.6 µm is a well-established, cheap and considerably good solution. The refractive optical elements are made of zinc selenide (ZnSe), which is most commonly used for this laser type. The diameter of the ring has to be adjustable between 0.5 mm and 2 mm. To create a sharp ring in the target plane, a high numerical aperture (NA) >0.35 (half angle of 20°) is used. Additionally, the system has to provide a constant ring diameter over the depth of focus, which means, that the system has to be telecentric on the sample side. The error of telecentricity is specified to be smaller than 1.5° for this work.

The generation of adjustable ring-shaped intensity distributions can be realized with different combinations of axicons and focusing elements [Rioux et al., 1978; Dickey et al., 2011]. Especially simple approaches are not able to create a sharp enough ring focus to precisely cut the polymer tape or the axial tolerance is too small. For this work a complex setup, which was applied to 1070 nm [Shao, 2006], is used as a starting point. Beneath the different working wavelengths, the need for telecentricity and the challenges associated with the spatial concept, especially the requirements for working distance and other mechanical dimensions had to be solved.

Figure 2 shows the simplified optical principle of the first ring-shaping unit, the axicon telescope pair and the final focusing group. The necessary beam expander, the optical staircase and the folding mirrors, which are indispensible for the adaption of the CO_2 laser ring-cutting system to the microscope, are neglected in this figure. Furthermore, lenses are replaced with paraxial lenses with short focal distances to create a compact sketch. In Figure 2 the optical path for two configurations is presented: The upper one for a small ring diameter (Figure 2a) and the lower one for a large ring diameter in the target plane (Figure 2b)). Essential parts of the design are labeled in the lower part of Figure 2.

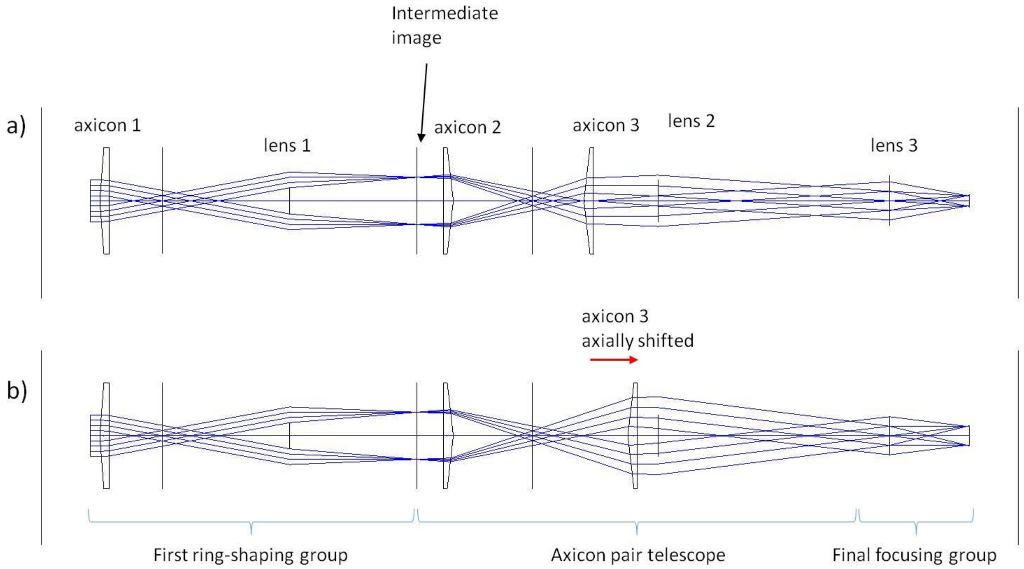

Fig. 2. Optical design of the first ring-shaping unit, the axicon telescope pair and the final focusing group for (a) a small ring diameter and (b) a large ring diameter.

The CO_2 laser beam passes the pilot laser coupling unit, the beam expander and the optical staircase and enters the ring shaping group with a diameter of 8 mm. A large diameter is needed to ensure large pupil filling of the final focusing group and thus, a high working numerical aperture. The first ring-shaping unit consists of a positive axicon (base angle α=0.5°) and a biconvex lens (f=150 mm). The axicon divides the incoming parallel ray bundles and deflects partial parallel ray bundles to the optical axis. The chief rays of the partial ray bundles cross the optical axis in the focal distance of the biconvex lens, which results in a telecentric intermediate ring focus after the lens. The following optical modules reimage this intermediate ring focus to the target plane.

The next optical group follows the intermediate image and is an axicon pair telescope, which consists of two positive axicons and a focusing lens and allows the adjustment of the diameter in the target plane. The diverging partial ray bundles coming from the intermediate image are deflected to the optical axis by a first axicon and cross each other. Afterwards they hit an axially movable second axicon (third axicon in the overall system) where they experience an additional change in propagation direction and hit a further lens. The front focal plane of this lens coincides with the preceding intermediate ring focus and thus, the partial ray bundles leave the lens parallel. Depending on the axial position of the axicon the chief ray height of the partial ray bundles on this lens change and due to this, the angles of the partial ray bundles leaving the lens change. In contrast the crossing point of the chief rays of the partial ray bundles and the width of the ray bundles are nearly independent from the axicon position. The axial position where the chief rays intersect is chosen as the pupil position of the final focusing group. As a consequence parallel ray bundles with adjustable chief ray angle are filling the pupil of the final focusing group with a constant diameter. This results in a telecentric ring focus for all adjustable diameters, which allows compensating height differences of the sample without changes in ring diameter. Furthermore, a constant numerical aperture for all adjustable ring diameters and a sharp ring focus is ensured. In this work, the numerical aperture of the partial ray bundles measures NA=0.375, resulting in a theoretically calculated Rayleigh diffraction limit of d=17.3 µm at λ=10.6 µm (with d=0.61 λ/NA). Beside optical aberrations the sharpness of the ring is mainly limited by the small depth of focus resulting from the high numerical aperture.

3. Results

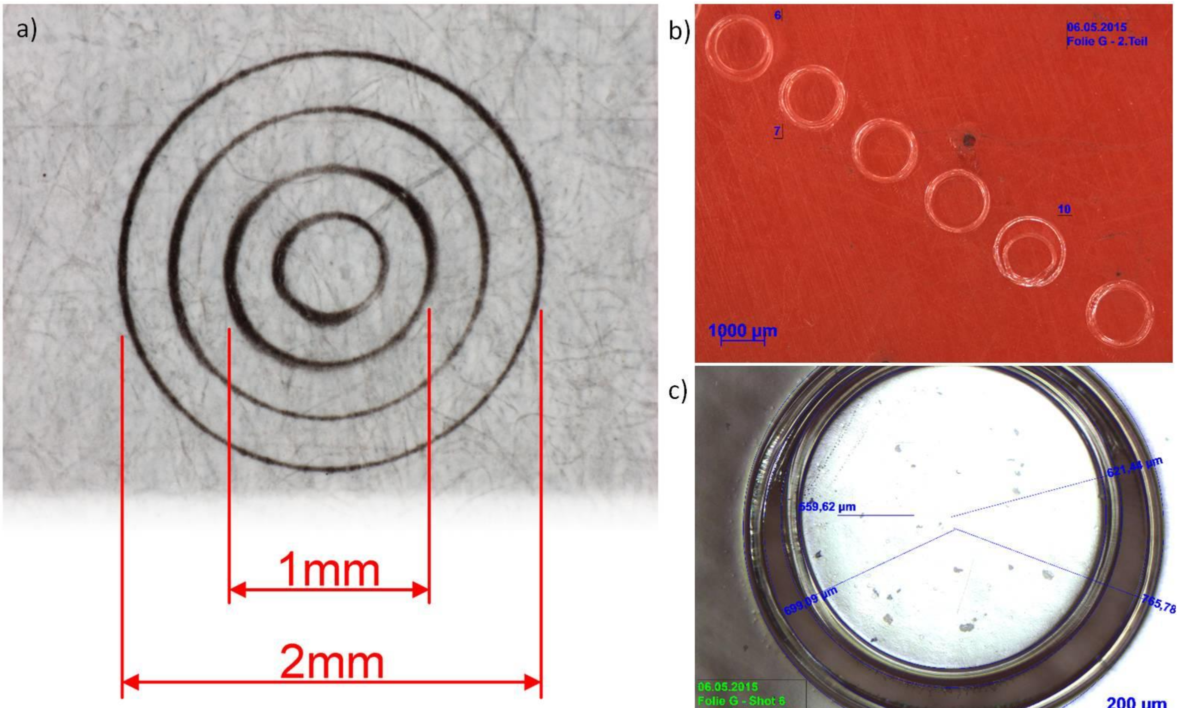

Fig. 3. a) Several rings on thermal paper with different diameters created by an axial shift of axicon 3 b) Cutting experiment on adhesive tape. c) Magnified sample after laser cutting. The polymer segment is separated from the polymer tape, but a small bridge prevents the loss of the sample.

The first experiments with the realized CO_2 laser ring-cutting system included tests of the basic characteristics. Thermal paper was irradiated with low power single shots to record the ring-shaped intensity distribution. In Figure 3a) a series of rings with different ring diameters in the range from 0.5 mm up to 2 mm are shown. The ring diameter is adjusted by an axial shift of the axicon in the axicon pair telescope. To create a comparable blackening of the thermal paper for different ring diameters, the number of pulses was increased for larger ring diameters.

The tests of the basic characteristics were followed by experiments on forensic adhesive tapes made of cellulose acetate. Traces were simulated with distributed dirt particles on the polymer tape. A target of interest is chosen with the observation microscope and subsequently cut out. Figure 3b) presents six cutting tests on a single polymer tape, which shows that a selected trace can be cut out and the rest of the polymer tape can further be investigated. The laser process was conducted with minimal laser energy. That's why a small connection remains visible, which is intended to avoid a loss of the selected target from the polymer tape. The sample was separated by tweezers and is shown in Figure 3c). By using a suitable target collecting mechanism, the bridging is not necessary anymore and can be avoided with slightly higher laser energy. Different materials and material compositions, tape thicknesses and ring diameters required single pulses or a few pulses (<10), pulse durations of a few milliseconds and pulse energies between 40 und 100 mJ.

Although the CO_2 laser ring-cutting system with adjustable diameter was developed for cutting forensic polymer adhesive tapes, other samples from the field of biotechnology can also be dissected with this setup for further examinations. The following section presents two exemplarily experiments. Figure 5a) shows a so-called biofilm, which is an aggregate of microorganisms, where the cells adhere to each other or the surface. A ring with a diameter of approximately 2 mm was cut out with 800 pulses, a single pulse energy of about 1 mJ and an overall process time of 8 ms. Another example is shown in Figure 5b), where the head of a bug is opened. The researches try to investigate the neural system of bugs in vivo. This extraction was conducted with 1000 pulses, a single pulse energy of approximately 2 mJ and an overall process time of 10 ms.

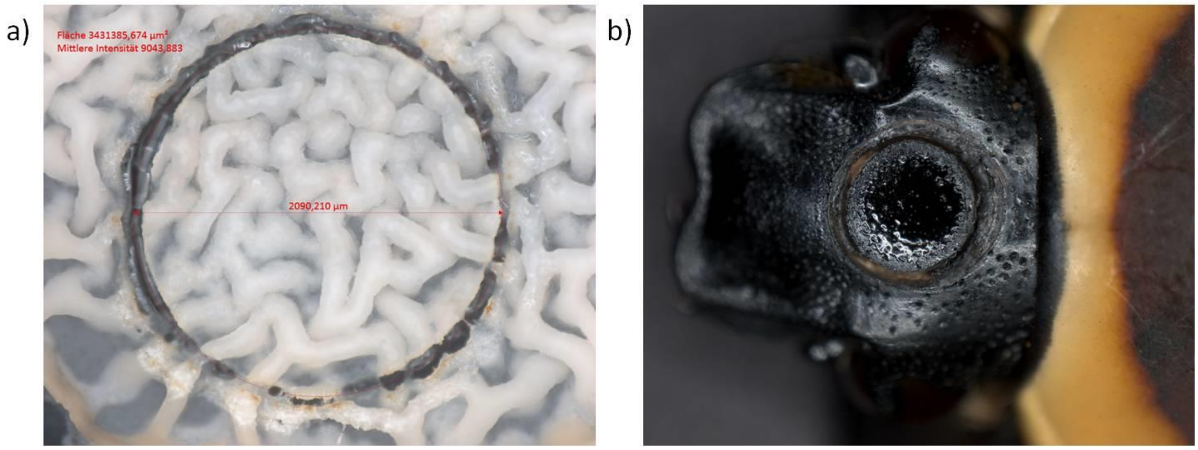

Fig. 5. Exemplarily samples which can be extracted for further investigations. a) biofilm. b) head of a bug

4. Conclusion

This contribution presented a CO_2 laser ring-cutting system at a working wavelength of 10.6 µm which is adapted to an observation microscope. The diameter of the ring can be adjusted between 500 µm and 2 mm. The system offers telecentricity in the target plane and a high numerical aperture to create a sharp ring focus with a width of less than 20 µm. The system was developed for cutting of forensic adhesive tapes, but the use for other dissection tasks in the field of biology and biotechnology was also demonstrated. The presented setup can be transferred to other wavelengths aiming on other applications.

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