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Flexographic and inkjet printing of polymer optical waveguides for fully integrated sensor systems

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Abstract

Planar optronic sensor systems are networks of integrated light sources, detectors and sensors, connected by optical waveguides on thin polymer films. This way, sensor networks can be realized completely optically for measuring quantities such as temperature, strain or chemical concentration. Applications unfold in structural health monitoring and chemical analysis. Waveguides represent a key element in this concept for signal transmission and the integration of interacting system components. The cost-effective and high-throughput production of polymer waveguides can be achieved by utilization of flexographic and inkjet printing. This particular application of the flexographic printing process is investigated for the first time and results show the suitability of the unique approach for production of waveguides with a minimum lateral dimension of 50 microns and parabolic cross sections. Inkjet printing is used as a complementary technique to deposit small amounts of materials at specific locations on substrates prestructured by flexographic printing. Additionally, inkjet printing allows for a thinner diameter of polymer waveguides if required, and new designs can be created easily as this process does not require invariable masks or printing forms. We show the structure of printed waveguides in layer systems consisting of core and claddings and discuss the challenges of additive manufacturing in a printing process. The resulting geometrical properties of the novel production process are described as the basis for a subsequent integration of sensors, sources, and sinks.

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Keywords: Waveguides; polymer; flexographic; inkjet; printing; multimode

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1. Introduction

Integrated intelligent systems require communication structures for collection and transmission of signals. Commonly, communication is carried out by means of a variation of the voltage applied to electrically conductive structures, which can be conducting traces or cables. These communication structures encounter technical limitations in terms of bandwidth, integration density, and due to their susceptibility to electromagnetic interferences. Optical communication systems, however, in this context are considered as enabling technologies, as they meet the growing demand for communication bandwidth with a significantly higher data rate than existing electrical systems. At the same time, such systems are characterized by a high integration density and a low error rate when subjected to electromagnetic interference.

The use of optical technologies in the field of sensing enables planar optronic systems (POS), which dispense with the conversion of measured quantities into an electrical signal, and instead, convert the measured quantity directly into a light signal. These sensor systems are fully integrated networks of light sources, detectors and sensors, connected by optical waveguides on thin polymer films. POS benefit from the mentioned advantages of optical communication and also offer a high flexibility and a compact design due to their geometry. Figure 1 illustrates a generic planar optronic sensor sub-system which features a laser diode as light source, and a photodiode as detector. The transmission path is created by a printed waveguide in which the actual sensor, a fiber Bragg grating, is integrated for strain measurement.

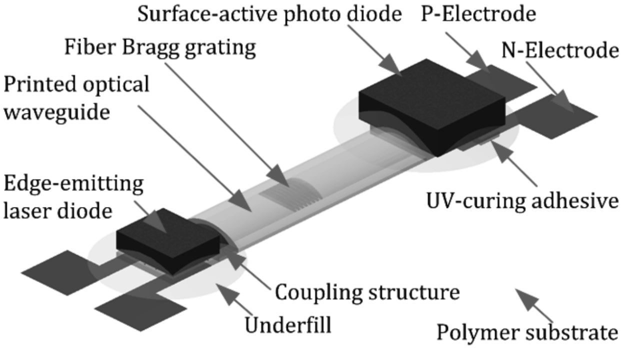

Fig. 1. Planar optronic sensor system (Yixiao Wang, ITA Hannover).

The waveguides in a POS transmit light signals in the wavelength range of 400-1200 nm and serve as the interconnection elements of the system in which the sensors are integrated. Measured quantities are, for example, temperature, strain or chemical concentrations, and the utilization of the sensor systems is carried out in, e.g., structural health monitoring, and chemical analysis. Printing processes are used as production processes for POS, and are suitable for mass production [1]. These processes of functional printing are particularly used for additive manufacturing of polymeric optical waveguides [2]. This is achieved by a variety of printing methods, in which transparent polymers are deposited locally in the liquid state onto substrates. A subsequent radical UV polymerization step hardens the printed layers.

2. Printed optical waveguides

There are different printing processes which vary in terms of the achievable throughput and resolution. Figure 2 orders the printing processes according to their measures of performance.

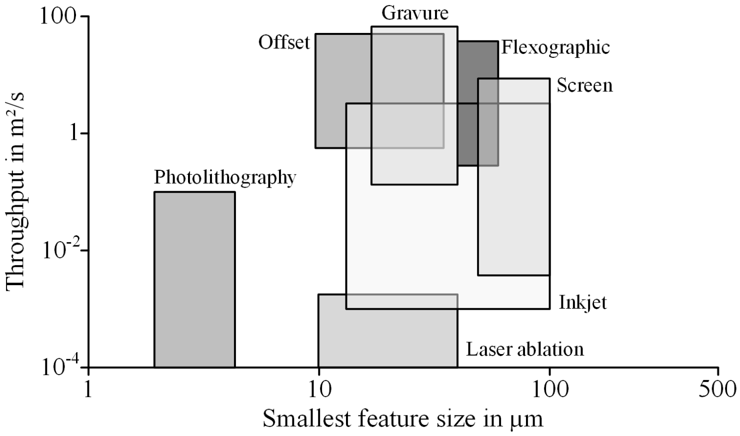

Fig. 2. Process limits of printing methods (cf. [3]).

Flexographic printing achieves a high throughput of up to 35 m²/s with a minimum feature size of 50 microns. In comparison, inkjet printing shows a lower throughput of 3 m²/s. However, a smaller structure width down to 15 microns can be generated [4]. For low-cost and high-throughput production of polymer optical waveguides, a combination of printing processes is used. Film substrates are initially pre-structured by flexographic printing and provided with optical waveguides. Inkjet printing is then carried out for individual complement of the waveguides to form coupling points, branches or protective layers. In this way, a process emerges that combines the advantages of high throughput and high resolution, which would normally be considered as conflicting objectives.

The propagation of light in waveguides is based on refractive index differences between the various material layers. For step-index profiles, the core of a waveguide must have a greater refractive index than the surrounding cladding structure [5]. From this requirement, four different types of possible configurations of printed waveguides result through a combination of core, cladding and substrate (see Figure 3).

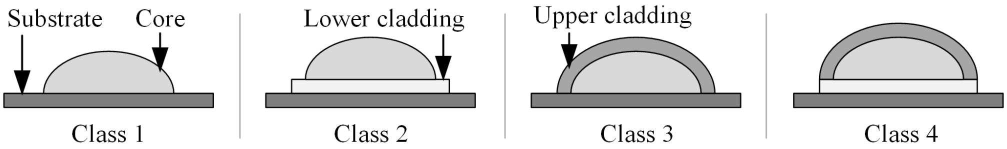

Fig. 3. Four possible waveguide configurations based on combinations of core, cladding and substrate.

The waveguides of class 1 consist of a core structure that is printed directly onto the substrate. It should be noted that the substrate and the atmospheric boundary must have a lower refractive index than the material of the core to ensure total internal reflection. For class 2, a lower cladding is placed between the core and substrate. In this way the dependency on the refractive index of the substrate is abolished because an intermediate layer can be chosen with a suitable refractive index. Similarly, the upper cladding in class 3 ensures that the light propagating in the core is not affected by changing atmospheric conditions. The greatest independence of refractive indices on the surrounding elements are attained by waveguide systems of class 4, which are fully surrounded with upper and lower cladding layers. For these waveguides, applications open up for atmospheric environments with arbitrary refractive indices, at the cost of more complicated processing conditions.

3. Flexographic printing

In the field of functional printing, flexographic printing has been used for the printing of electrically conductive structures [6], while presently the expansion to the printing of light-guiding structures is carried out [7]. In this continuous printing process, three cylinders roll off each other (see Figure 4 a). An anilox roller with engraved cell structure on the perimeter first collects liquid polymer from a chambered doctor blade. On the perimeter of a second cylinder, an invariable printing plate with elevated structures on the surface is applied. During contact of the printing form with the anilox roller, the structures of the printing plate are wetted. The printing form cylinder then rolls on the impression cylinder and generates a mirror-inverted image of the printing plate on the substrate.

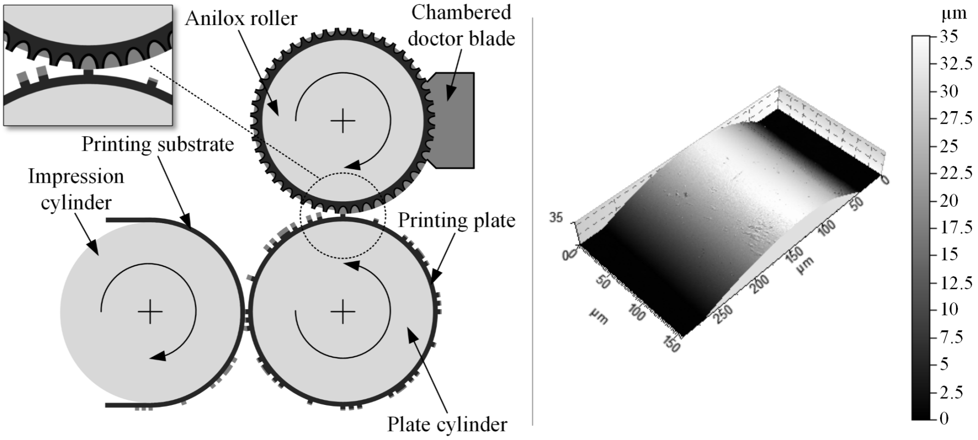

Fig. 4. (a) Operating principle of flexographic printing system; Detail: wetting of printing plate; (b) Confocal microscopy of flexographic printed waveguide.

For printing tests, a modified industrial printing machine was used with two printing units for offset and one for flexographic printing (Heidelberg Speedmaster 52). A photopolymer (Flint, Gold A) served as printing plate with structures of different line width between 50-1,000 microns. An acrylate (Jaenecke+Schneemann Druckfarben, UV Glanzlack praegefähig) transparent polymer has been used with a dynamic viscosity of 200 mPas at a temperature of 26°C and a shear rate of 100 s^{-1}. At a constant infeed of the printing plate to the substrate, ten printing cycles have been conducted, and line structures where printed over one another in layers (cf. Fig. 4 b). During the course of printing cycles, the layers where subject to a height increase of 3.45 microns on average, while the width of the structure remained relatively constant. Figure 5 a shows the course of the layer width and height after each printing cycle.

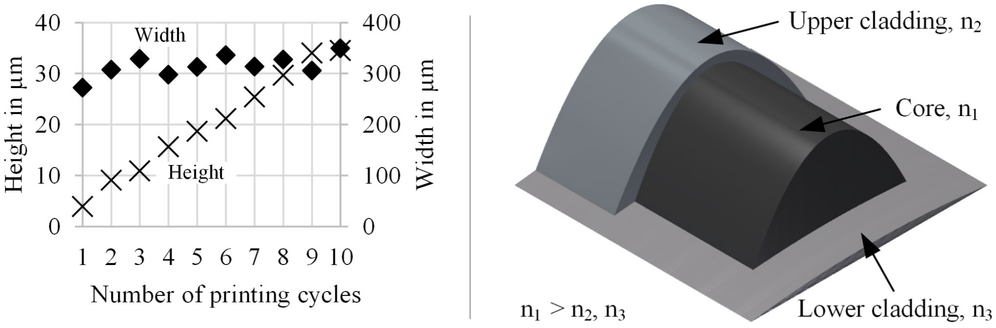

Fig. 5. (a) Height and width of printed waveguides versus number of printing cycles; (b) Computed 3D model of printed waveguide generated by second order parabolas; section view.

Dome-like structures are observed as characteristic cross-sectional shapes, and can be approximated sufficiently accurately using parabolas. Figure 5 b shows the computed geometry of a printed waveguide out of class 4, and was generated by a set of second order parabolas. Already at this polynomial order, the coefficient of determination R^2 is 0.99903. In particular, the overlap areas from the substrate to the lower cladding structure, as well as possible surface undulations, require higher-order functions for the approximation.

Since the individual printed layers have a limited height, multiple printing passes are sometimes needed to achieve the desired height. In this case, a reasonably accurate lateral positioning of the substrates in the printing machine is required. It is assumed that the positioning accuracy should be less than 1/10 of the line width in order to render the central areas of the printed lines useful. The printing machine used provides an automatic sheet correction, which ensures the required positioning accuracy within the range of printable line widths.

As the lower limit of printable line width, the minimum feature size in the engraving process of the printing plate was determined. Photopolymers with oxygen inhibition (Flint, Gold A) show a minimum pattern width of 68 microns, whereas photopolymers without oxygen inhibition (Kodak, Flexcel NX) can achieve a minimum width of 10 microns. The upper process limit of the line width is limited by viscous fingering [8], which was observed for a line width of > 900 microns. The consequence of viscous fingering is an increase of surface undulations, which leads to falling below the critical angle during light conduction, and thus a larger attenuation of the waveguide. For this technology and setup, a line width between 250-450 microns has been determined as ideal.

4. Inkjet printing

For situations where flexographic printing is unsuitable, inkjet printing is employed as a complementary process [9]. The technique is based on the controlled ejection and deposition of individual droplets with a volume between 1-1,000 picolitres from a position above the substrate. This is one of the main advantages of this technique – the defined, yet contactless deposition of material under normal atmospheric conditions. The working principle implies that substrates, which are prestructured with other optical elements, can be furnished with inkjet printed structures relatively unproblematically. Additionally, the process has a high geometric flexibility, as new printing patterns can be created on the substrate without any intermediate steps. In this project, a widely-used research desktop printer (Dimatix DMP 2831) is employed to deposit the experimental inks (InkOrmo and InkEpo, Microresist Technology) intended for optical applications.

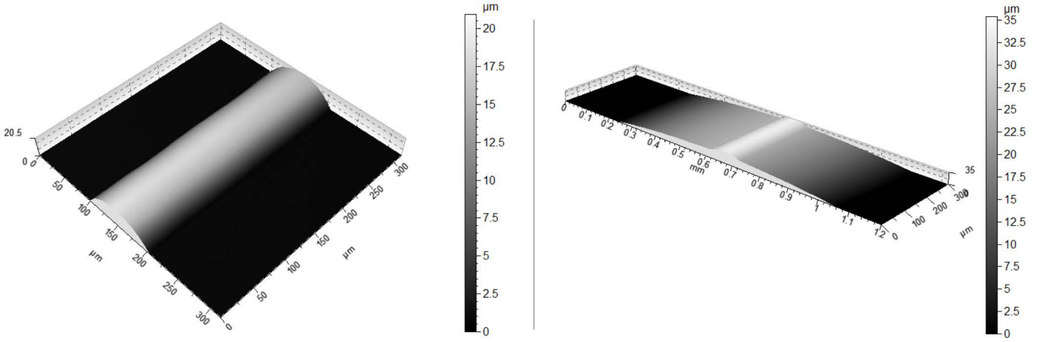

Fig. 6. Images of inkjet-printed waveguides taken by confocal microscopy (a) Uncladded class 1 waveguide; (b) Class 4 waveguide including lower and upper cladding.

To demonstrate the feasibility to create optical waveguides with inkjet printing, two types were manufactured on PVC-foil - one with a class 1 cross section, and one with a class 4 cross section. An image of these structures obtained by confocal microscopy is shown in figures 6 a and b. It was found that a high substrate temperature led to higher cross section aspect ratios for either inks, and hence a technique which could be used to control the shape of the printed structures. InkEpo, which was used to create the waveguide core, was printed onto a substrate secured on a flat hotplate. The entire assembly was placed inside the printer and operated at elevated temperatures to achieve a high aspect ratio. On the other hand, the cladding should ideally be flat and broad. Therefore, InkOrmo, having the lower refractive index, was printed at room temperature to allow it to spread across the substrate. For uncladded waveguides, an aspect ratio of 20 microns/100 microns was possible, for cladded waveguides a core aspect ratio of 10 microns/100 microns resulted. The process parameters to achieve these profiles are described in Table 1.

Table 1. Material and process parameters for inkjet printing of optical waveguides.

Waveguide Component	Ink	Refractive Index n_{D20}	Printhead Voltage	Printhead Temperature	Substrate Temperature
Core	InkEpo	1.555	25 V	40°C	70°C
Cladding	InkOrmo	1.515	40 V	40°C	25°C

Subsequent to printing, the inks were cured by UV-radiation with an UV-light source (HP-120) for 10 seconds exposure. During the experiments, it was found that the polymerization of InkOrmo is inhibited by oxygen, which made it necessary to print this ink under inert nitrogen atmosphere conditions.

After the general suitability of inkjet printing to create optical structures was demonstrated, the compatibility of both printing techniques was investigated. While flexographic printing is able to pattern large areas within seconds, the slower inkjet printing process proves a spatial higher resolution and therefore allows to form finer structures, and also is much more suitable to deposit special inks at specific places. Situations where this combination of techniques is advantageous are, for example, inkjet printing of the waveguide core on top of flexographically printed cladding structures, or to connect flexographically printed waveguides with other optical elements, which have been added to the system subsequently. Another option is to create optical light sources directly by inkjet printing on the substrate.

The main challenge to combine both techniques is to match the wetting behavior of the inkjet printed ink to all contacted surfaces. When printed on untreated flexographic prints, neither InkEpo nor InkOrmo are compatible and show random spreading and a tendency to form bulges. This problem was solved by placing the substrate in an oxygen plasma (Diener Femto O2) for one minute to activate the surface, which causes the ink to wet the substrate better. After this treatment, the contact angle of the ink on a room temperature substrate changes from 11.5° to 2.6°. Longer plasma treatment causes the ink to spread out even further on the substrate, leading to exceedingly low aspect ratios.

5. Discussion

The current results show that it is feasible to deposit materials for polymer optical waveguides on flexible substrates by both flexographic and inkjet printing. We achieved geometric dimensions of 100 microns wide and 50 microns high for flexographic printing, and a width of 100 microns and height of 20 microns for inkjet printing. This implies aspect ratios ranging between 0.1-0.2 for inkjet printing and a maximum of 0.5 for flexographic printing. Selviah et al. report that aspect ratios can be increased for inkjet printing with repeated consecutive steps of printing and UV-curing, as it is performed for flexographic printing [10].

A major difference between the two printing techniques is the compatibility to other processing steps. While inkjet printing is contact free and can still be performed after the substrate was furnished with other structures and elements in previous processing steps, flexographic printing requires direct contact between printing cylinders and substrates, causing all structures and elements which are placed there before to experience considerable compression forces. Therefore, flexographic printing needs to be conducted before other patterning steps are performed. Inkjet printing, on the other hand, is much more flexible in this concern because it is contact free. This means that inkjet printing can possibly be the last processing step in a production sequence.

POS require that the formed waveguides must be coupled to discrete system elements such as diodes and sensors. Here, we consider light sources, as this element is important for both optical characterization and the coupling to laser diodes. Figure 7 a shows the coupling condition in an optical measurement setup that is used for waveguide characterization. Here, a beam spot with a diameter of 100 microns is focused on the end face of a printed waveguide core.

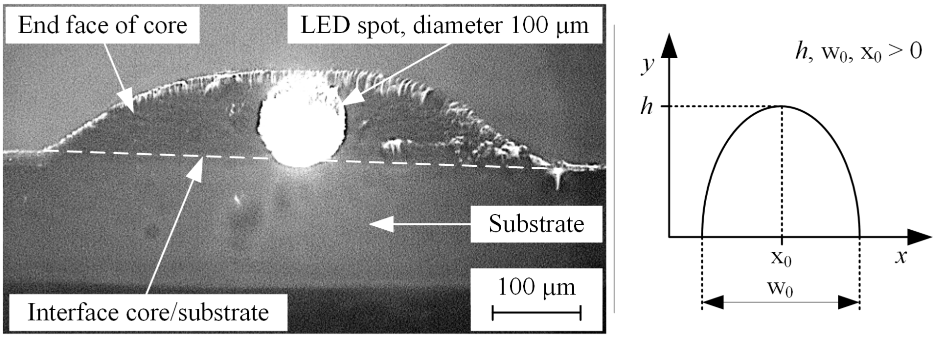

Fig. 7. (a) End face of printed class 1 waveguide (height 100 microns, width 600 microns) in an optical measurement setup with a focused LED spot and interface core/substrate; (b) Geometrical features of a parabolic waveguide model.

The printing process results in a parabolic geometry of the individual layers. Since the width of the waveguide remains constant during multiple pass printing, it is possible to determine the approximate height of the waveguides from the number of printing cycles. The aspect ratio *AR* describes the relation of height *h* and width *w* of the printed structure:

$$AR = \frac{h}{w} \tag{1}$$

This means that, by increasing the number of printing cycles, the aspect ratio of the waveguides also increases. With this possibility of shaping the geometry, the question arises as to which aspect ratio should be generated with regard to an optimized coupling of light. For the investigation of this relationship, two assumptions are made. First, the cross section of the core structure is described by a parabola of second order. By this assumption, any relationships are valid for all four classes of waveguide geometry. Second, it is assumed that the shape of the beam spot is circular and the entire spot remains within the limits of the core structure at all times. Thus, the effective area of the core profile is used optimally in this arrangement and the optical power, which is directly proportional to the beam spot area, is coupled with low loss.

To describe the core profile, the constant width w_0, the x-coordinate of the vertex x_0 and the height *h* of the core are used (cf. Figure 7 b). From the vertex form of the parabola, the function values $y(x)$ are:

$$y(x) = h\left[1 - \left(\frac{w_0}{2}\right)^{-2} \left(x - x_0\right)^2\right] \tag{2}$$

A waveguide featuring a constant width w_0 of 200 microns at a variable aspect ratio ranging from 0-1.0 is considered and the resulting effective beam spot area is determined. Figures 8 a-c show the geometric proportions of the consideration and Figure 8 d depicts the course of the effective beam spot area over the aspect ratio.

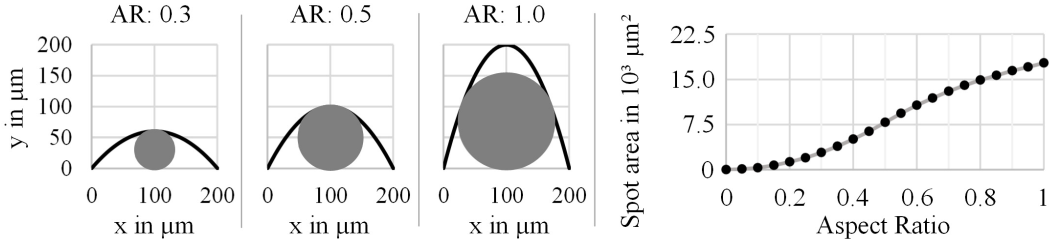

Fig. 8. (a) – (c) Circular beam spot is fitted within the example waveguide geometry at different aspect ratios (*AR*); (d) Effective beam spot area vs. aspect ratio of waveguide.

It is found that the beam spot area increases quadratically with the aspect ratio over the range 0-0.5 and is degressive in the range 0.5-1.0, but increases monotonically over the entire range. This demonstrates that an increase of the aspect ratio results in an increase of the effective beam spot area and therefore leads to a maximization of the coupled power. However, the effectiveness of this measure is particularly large in the range of 0.4-0.6, whereas it decreases thereafter. On the basis of this correlation, coupling structures for light sources can be optimized.

An interesting alternative to face coupling is to utilize inkjet-printed micro lenses as coupling structures [11]. As the behavior of the inks can be well controlled by means of temperature and plasma, lenses with desired curvatures can be created at arbitrary positions on the substrate [12]. These lenses can be used at the end of a waveguide to focus the light to match the numeric aperture of the printed waveguides.

6. Summary and Outlook

In this report, we investigated whether the additive manufacturing techniques flexographic and inkjet printing are suitable to create polymer optical waveguides as central elements of planar optronic systems. The results show that both methods allow to manufacture structures which can be employed as optical waveguides. A combination of the high-throughput flexographic and the variable inkjet printing results in a process chain that allows for mass production of the described elements for sensor systems.

The geometric relationship for coupling of light sources with a circular beam spot area to parabolic shaped waveguides has been discussed. It was shown that the increase of the aspect ratio in the range of 0-1 enables a low-loss coupling. However, the efficiency of increasing the aspect ratio to lower the optical attenuation varies in the course of the aspect ratio. The greatest efficiency of this measure occurs in the range of 0.4-0.6.

The current challenges are mainly to find a suitable method to couple light into the structures, either by achieving a high aspect ratio in the printing process, or by furnishing the waveguides with printed micro-lenses. This will then allow an attenuation and dispersion analysis of the printed structures, along with first complete emitter - sensor - detector setups. The results of these investigations will be presented in future work.

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