Direct Writing of Light Guiding Structures

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Abstract

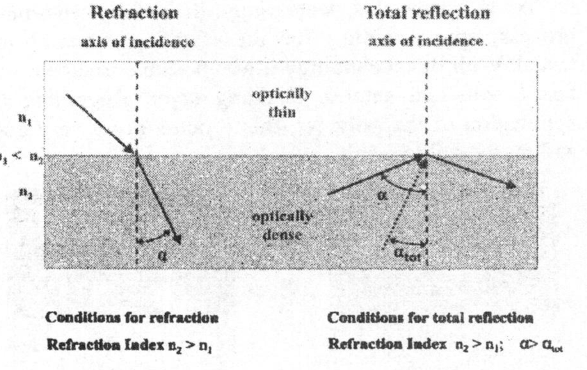
The application of optical structures in data transfer and measurement increases steadily. Optical fibres in WAN (Wide Area Networks) and LAN (Local Area Network) are state of the art. Polymer optical fibres (POFs) are superior to electrical conductors due to their lightness, their resistance to damage and electromagnetic interference. Just like their glass equivalents they provide a high data transfer rate. The integration of light guiding structures on and in surfaces with the help of dispensing technology is considered in this paper. In the first part the properties of optical fibers are described. The available structures and the integration in components lead to the direct creation of light guiding structures in and on surfaces. For achieving this, one polymer is applied on the surface in order to build the cladding. In the next step another polymer is filled in or on the cladding and sets up the core of the light guiding structure. An additional layer of the first polymer encloses the core.

Keywords

direct writing of light guiding structures, optical polymer, optical fiber, dispensing technology

Basics of optical fibers

The function of optical fibers is based on internal total reflection. Total reflection occurs on a light path from an optically denser to an optically thinner medium, if the angle of incidence alpha is greater than the critical angle alpha total.



Picture 1 Refraction and total reflection

The angle α_{tot} represents the arcsines of the quotient of the refraction indexes of both materials. Every light ray with a greater angle than this is totally reflected at the boundary layer of both materials. The reflected light ray is led theoretically lossless within the fiber and allows the realization of very large transfer distances. For the production of optical fibers a cladding and a core with different refraction indexes are needed [1]. The difference between both refraction indexes has a direct influence on the acceptance cone of the fiber. This angle of the acceptance cone influences the signal transmission rate because of the mode-dispersion. Additionally, the preparation of the surfaces and the exact positioning of the transmitter and receiver are very important for the signal strength and data transfer rate [2].

There are two different transmission types in a polymer optical fiber. The first one is the step index profile fiber. A step index profile fiber consists of a highly transparent core and a surrounding cladding. Both materials have different refraction indexes. To ensure that a light ray, which has entered the fiber, can be guided along the fiber the cladding needs a lower refraction index than the core. The cladding material we tested had therefore a refraction index of 1.438. The profile of the refraction index over the diameter is a stepped function (this is where the name is from). The step index profile fiber is normally used for short but cheap transmission routes with a normal data transfer rate.

Another principle for the implementation of light guiding is the graded-index profile fiber. In contrast to the step index profile the refraction index changes depending on the fiber diameter. Therefore the light ray is refracted constantly and has a bended light path. The graded-index profile fiber is used when longer transmission routes in combination with higher data transfer rates are needed. There are more fiber types especially when glass is used as a core material.

Optical wave-guides as interconnects in photonic packages for data- and telecom as well as for sensors are still a research topic. Hot embossing and lithography produce such wave-guides. Laser technology is also used to create optical structures. The concept is the integration of multimode wave-guides into a thin optical foil that can be laminated into a printed circuit board (PCB) [3/4].

Until now, available systems are not supposed for the direct integration into components and the direct connection of optical structures and electro-optical devices [5].

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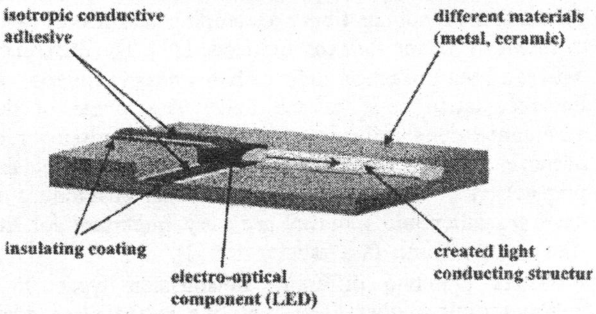
Motivation

The main motivation for this project was the integration of electro-optical devices directly into metallic components. Moreover, the aim was a high data transfer rate, a resistance to electromagnetic radiation and a potential separation. Therefore the target was to integrate an electro-optical component, for example a LED (as transmitter), in or on the surface of different materials. This electro-optical component is connected with isotropic conductive adhesive [6] on an insulating coating. After that, the transmitting component will be connected directly to a similar receiver device with the help of a light guiding structure. An overview about this is shown in the following picture 2.



Picture 2 Direct created light guiding structures

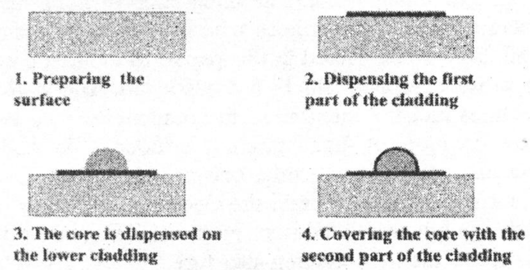
During the handling of normal optical fibres it is important to cut and polish the optical fibres before connecting them to other components. The connection of directly dispensed structures is much easier. Because of the liquid processing the transmitter and the receiver can be connected without special preparation.

Required material characteristics

One aim of the study was to identify materials suited for the planned process. The required material characteristics are divided into three sections, the optical, mechanical and handling characteristics. As already mentioned the main optical characteristic is the refraction index. This should be about 1.438 for the cladding and between 1.5 to 1.55 for the core material. Of course the transmittance should be 100 % for the guided wavelength. The most important mechanical characteristic was the resistance against the estimated stress. Therefore the temperature resistance should be from – 40 °C to 120 °C. Another point for the choice of material was the handling characteristics. For the cladding material the viscosity should be very low. For the core the polymer should have a low viscosity for the trench structure and a very high viscosity for structures on the surface. The adhesive should be a one component Epoxy resin, which cures under UV-light. With the selected materials two different structure types were created.

Technical implementation

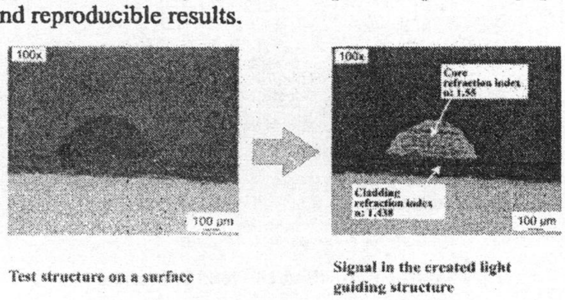
One structure type is created on the surface. In a first step the surface is prepared and every possible mark has to be removed. In a second step, the first part of the cladding is dispensed directly on the component's surface. Small scratches and roughness in the surface can be compensated by the surface tension of the cladding material. After the curing of the cladding the core is dispensed on the lower cladding. The core material has to be jelly-like with a very high viscosity to keep it in form. Highest demands are made on the structure of the core with regard to the regularity and the geometric dimension. These requests are fulfilled by a constant dispensing speed as well as a constant dispensing amount. After curing the core it has to be covered with the second part of the cladding. Now the cladding is closed and enables the light guiding.



Picture 3 Creating of light guiding structures on surfaces

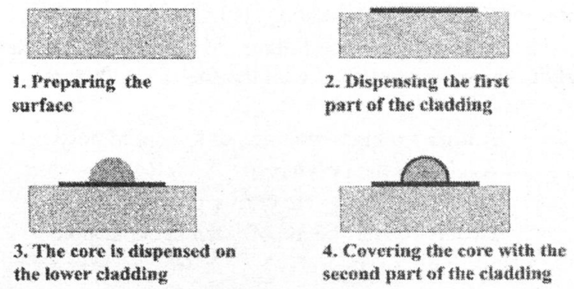
With this technology, it is possible to create structures of approximately 400 μm widths and 250 μm heights. The viscosity of the core is proved to be the main process parameter during the dispensing [7]. The cladding has a viscosity of 20 mPas and a refraction index of 1.438. The jelly-like polymer of the core has a viscosity of 10000 mPas and a refraction index of 1.55 and can be applied on sloped surfaces without flowing. The described method is independent from the geometries of the component, as long as the acceptable bending diameter does not fall below the critical angle alpha total. A smaller bending diameter causes an optical leak and the light emits.

To integrate this technology in a fully automated process, spray coating for the cladding material was tested. With this technology it was possible to create very fast a thin and smooth cladding layer. Regarding the application of the polymer, this process gives very good and reproducible results.



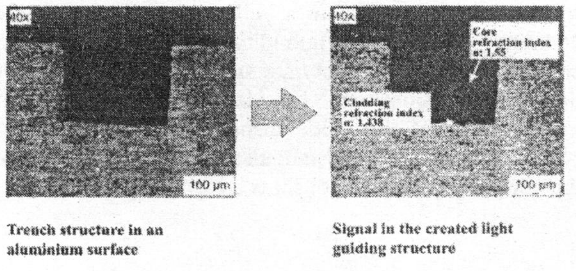
Picture 4 Light guiding structures on surfaces

For the production of a light guiding structure that is integrated into the device, a trench-structure is milled in the device. In a second step the first part of the cladding is dispensed in this trench. Due to the low viscosity and the surface tension the adhesive is allocated regularly in the trench. In a third step the core material is filled in the cured lower cladding. By covering the core with the second part of the cladding the structure is closed. After each step the applied polymers have to be cured with UV-radiation.



Picture 5 Creating of surface integrated light guiding structures

The advantage of this method is the highly defined geometry of the light guiding structure inside the trench. In further tests, we created directly lighting splitter structures. Generally, the integration of a light guiding structures in the surface protects the structure against mechanical forces and guarantees a direct connection of the light guiding structure with the device. The best results were achieved by using polymers with a very low viscosity (20 – 80 mPas). These polymers were able to compensate possible irregularities and bubbles during the dispensing-process due to the capillary effect within the trench structure.



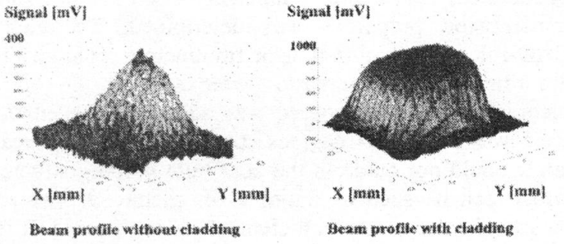
Picture 6 Surface integrated light guiding structure

Additionally to the previously described technology a double stepped structure was created in the surface. Therefore three different optical materials were used. Two cladding materials with a refraction index of 1,438 and 1,50 were applied in the trench structure. These two lower cladding layers were filled with the core material. The polymer for this core had a refraction index off 1,55. With further dispensing processes the two cladding layers were closed. The idea for this process was a signal transmission improvement of the created structure. Because of the second cladding the structure should provide a better light guiding in a bent structure. A light ray in this bent structure which is not totally reflected between the core and the interior cladding is totally reflected between the two outer cladding layers. A similar technology is also used in polymer optical fibres were it is known as double step index polymer optical fibre (DSI-POF) [1].

Structure properties

The properties of light guiding structures can be used over a distance that is easy to evaluate. The information to be transmitted is generally supplied in form of electrical signals. Often it must be supplied at its destination in this form. Transmission along a polymer optical fibre thus requires the use of transmitting and receiving components for electrical/optical conversion and the opposite conversion at the end of the link. One influence for the data transmission rate is the mode dispersion. This mode dispersion is the result of different light path lengths in the optical fibre. A straight light ray needs less time than a diagonal light ray. Therefore the input pulse does not reach the receiver at the same time. It is thus easy to calculate the theoretical data transmission rate according to the numerical aperture and the length of the fibre. For example the theoretical transfer rate of a 10 meter fibre with a numerical aperture off 0.578 is over 100 Mbit/s.

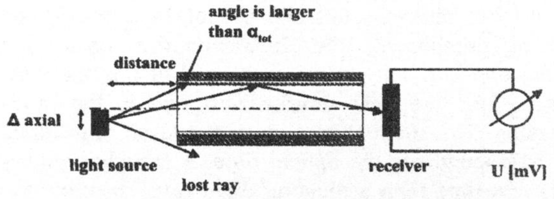
To make sure that the light is led through the fibre due to total reflection, the influence of the cladding material in two different straight structures was examined. One structure was produced without and the other structure with a cladding.



Picture7 Influence of the cladding material

The test showed that the beam profile without a cladding has a much lower value and only a small peak area. The output of the receiver unit had a voltage of 350 mV. Contrary, the structure with the cladding is able to guide the light, consequently it has a higher output value and a greater peak area. The output of the receiver unit hereby had a voltage of 800 mV. Other tested structures were bended and split structures. The bending diameter was up to 35 mm and the structure size was from 2.0 mm to 0.7 mm. A splitting angel up to 30° was implanted in the splitter structure. The length of both structures was about 150 mm; in both cases the light signal could be led through the structure. Of course the strength of the transmitted signal was reduced. Compared to the straight structure, over 60 % of the signal is led through the 35 mm bending diameter. Attenuation was measured by cutting slices from the structure and comparing the output power. This procedure is known as cut-back-method. The attenuation is in a range from 0.11 to 0.16 [db/cm].

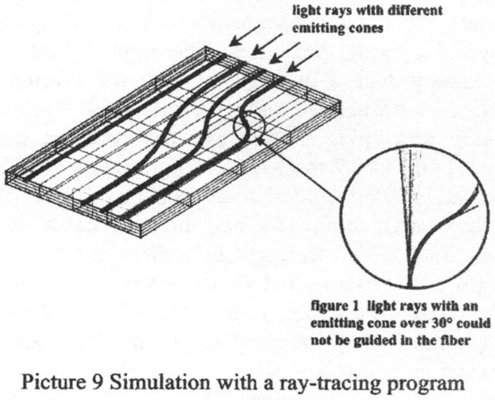
The connection of the electro-optical components and the light structure is a main source of losing signal strength. To test the requirements for the alignment of the electro-optical components the transmitted signal strength was measured while changing the axial position of the signal source in the X and Y Axis. The measured signal value shows a nearly constant plateau with a width and height of 600 µm. The structure had a dimension of 800 to 800 µm, which means that a LED chip is easy to connect.



Picture 8 Influence of the misalignment of electro-optical components and light guiding structures

During the handling of normal optical fibres it is an important work step to cut and polish the optical fibre before connecting it to another component. The connection of the directly created structures is much easier. Because of the liquid processing the transmitter and the receiver can be connected without special preparation.

With a ray tracing program the influence of the geometrical structure dimension on the signal transmission properties was determined. Therefore a CAD-File was imported in a ray-tracing program. The described optical properties were set for the optical material and a light source was adjusted. The emitting cone was set to 30 degrees. Light rays with a greater angle could not guide in the bent light guiding structure, which can be seen in figure 1 off picture 9. The path length of 36 rays for each channel was compared. It was possible to determinate the theoretical data transmission rate for the structure in and on the surface. The light path time difference for the bent structure with a length of 1 m was 0.5 ns. With this short signal dispersion it should be possible to achieve a high data transfer rate.



Picture 9 Simulation with a ray-tracing program

Reliability

For reliability tests the created structures were exposed to changing environmental conditions. The temperature was changed from –40 °C to 120 °C and the air humidity was changed up to 95 %. The first selected polymers, which had good transmission properties, failed in this test. Stress and low durability are the main causes of optical adhesive failure. Shrinkage on cure, ageing or thermal expansion creates this stress. High temperature curing of many epoxies can thus create internal stress on cool-down to room temperatures [8].

The reason for the failure of the first selected polymers can be explained with the following factors:

- A high Young's modulus of the cured polymer
- Ageing of the polymer
- Shrinkage during the curing process
- Different coefficients of thermal expansion

A combination of all this factors produces a high internal stress in the created structure. The internal stress exceeds the material properties and cracks occur in the created structures. A crack in the light guiding structure reduces the transmitted signal strength to nearly zero. To avoid these effects other polymers had to be chosen. The best result was produced with a very low Young's modulus between 13 - 21 N/mm² for the polymer. This polymer had also a very low shrinking effect. Due to the low Young's modulus the polymer could also compensate the internal stress caused by different coefficients of thermal expansion.

Another effect of the moisture and temperature cycles is the simulation of the polymer ageing. The water clear structures changes into in a yellow clear structure after 24 hours, 95 % relative humidity and 90°C. Due to this change in the internal polymer structure the effect on the data transmission rate has to be determined. The measurement of the mode dispersion in the optimised structure for a 5 Mhz rectangular signal before and after the climatic cycle does not show a recognizable change.

Conclusions

With the presented technology, a light guiding structure can be created directly by using dispensing systems. These structures connect the transmitting and receiving units with the help of liquid optical materials. A preparation of the fibre is not necessary. The technology can be integrated in a fully automated process. For future applications, the light guiding structures can be integrated in automotive technology. It is also possible to create optical sensors, such as extension or temperature sensors by using the described technology. It is planned to develop a screen-printing process for light guiding structures for low cost applications and complex structures.

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