Level 1 optical interconnects – a pathway to volume manufacturing

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Abstract

Super computing is reaching out to ExaFLOP processing speeds, creating fundamental challenges for the way that computing systems are designed and built. The governing topic is the reduction of power used for operating the computer system, and eliminating the excess heat generated from the system. Current thinking sees optical interconnects on most interconnect levels to be a feasible solution to many of the challenges, although there are still limitations to the technical solutions, in particular with regard to manufacturability in high volume. An optical interconnect solution is proposed that allows the creation of optical components on module level, integrating optical chips, laser or PIN diodes as components much like the well-known Surface mount devices and components used for electrical assemblies. The paper shows the main challenges and its potential solutions, and it proposes a fundamental paradigm shift in manufacturing by using 3-dimensional optical links for the level 1 interconnect enabling high-volume manufacturing of optical packages for datacom applications.

1 Manufacturing of Optical Interconnects

1.1 State-of-the-art waveguide manufacturing

The creation of optical interconnects has been addressed by many groups in the past two decades, mainly in the form of optical waveguides (OW). Therefore, many different technologies have been explored for manufacturing optical waveguides, like photolithography [1] , hot embossing/micro molding [2], laser ablation [3], nano imprint lithography (NIL) [4], laser direct writing [5], and non-linear optics using two-photon absorption (TPA) polymerization [6, 7].

These waveguide manufacturing technologies can in principle be used for achieving optical connectivity, but it will be hard for many to survive the process of upscaling them to high volume manufacturing. This is true not only for multi-mode waveguides, but in particular for single-mode waveguides manufacturing techniques. The prime reason is the required high precision of the alignment of the optical components to the waveguides. Typical challenges are process speed, component-to-waveguide alignment and test.

The complete physical layer of the system architecture and its implementation through the manufacturing process of an optical interconnect has to be taken into account when optimizing an optical interconnect solution. While some of the waveguide manufacturing process technologies have reached a level of sophistication that would allow the transfer to volume manufacturing of optical waveguides, practical topics remain in the value chain that need to be solved. As minimum requirement, the features include the drivers, electric-to-optical (E/O) and optical-to-electrical (O/E) conversion components as well as the light source and the detector, and the waveguide.

State-of-the-art assembly equipment is capable of handling substrates and dies. The higher the precision gets the slower the assembly process is, and it is very slow when sub-micron precision is required, like in an optical assembly with single mode connectivity requirement. This is critical for scaling to large volumes of product. In addition, the alignment of multiple I/O coming from an optical arrangement, an optical chip, or a laser bar will be even harder than for a single I/O if traditional technical solutions are taken into account. Active alignment is the current state-of-the-art in assembly of such optical arrangements. The device needs to be powered up and emit/receive light like during live operation. Passive alignment is preferred as it is cheaper and faster to implement and operate in a manufacturing environment.

1.2 Requirements for optical interconnects

The understanding of the requirements of optical interconnects has been advanced over the past years, and the main challenge has been addressed: creating optical interconnects (OI) that can be manufactured in larger volumes in an economically viable way. The insights were mainly driven by telecom and datacom applications, propelling the development of OI strategies that would allow manufacturing of optical or optoelectronic systems to be done similar to the way that electrical systems are built today [8]. In specific, the challenges for advancing optical technology closer to the Printed Circuit Board (PCB) and chip package, or into packaging levels one (chip or component package) and two (circuit board assembly) are in focus. Interconnect level 0, the optical interconnect on the chip itself, is also being addressed.

To understand the challenge better, a look to the electronics manufacturing services (EMS) industry is helpful. Scaling of manufacturing of products to very high volume manufacturing has been demonstrated over the past 20 years by this industry, in particular for mobile devices. There are plenty of examples how innovation in miniaturization and integration enabled new features in mobile consumer products and supported volume manufacturing: a) the advent of surface mount technology (SMT) enabling faster assembly, b) shrinking components for enabling thinner buildups on a smaller footprint, c) the use of various generations of area array technology (Ball grid arrays, land grid array, …) allowing the reduction of number of assembled components, and d) stacking of components to die stacks, yielding highly integrated system-in-packages, to name a few. Electronics manufacturing has come a long way of putting more computing power into silicon, and more integration capability into level 1 and level 2 packaging, respectively.

If this development is taken as a role model for the optoelectronics industry paradigmatic shifts in the view on connectivity between the different physical interconnect layers appear. Enabling the OI to be efficiently manufactured will allow optical technologies to advance into interconnect levels 0 to 2. By extending the approach described above, various alternatives of interconnecting components on different interconnect levels can be considered. We propose a technology that allows the interconnection of optical components within a component package in a standardizable fashion, allowing the use of existing infrastructure for assembly, for scalable manufacturing of optical component packages (OCP).

2 New manufacturing process for optical component surface mount assemblies

2.1 The need for scalability of optical interconnect manufacturing

Existing manufacturing processes for optical waveguides have not been able to meet all requirements for high volume manufacturing of integrated optical modules. To equip future data centers with optical technology on a chip level, high volume manufacturing of chips, chip packages and assemblies must be developed. A new interconnection technology and manufacturing process flow has been developed that allows the elimination most of the drawbacks of existing processes and that is scalable to volume manufacturing. In addition to the new way of creating the waveguides, a fundamental paradigm shift for the process sequence for the assembly process is proposed. The proof of concept has previously been shown in several arrangements [9], and this new implementation will allow the process to be used for creating optical components that can be used like electrical modules during assembly, while exhibiting the function of optical modules. Figure 1 shows a schematic representation of such an optical component module.

The 3D waveguides allow optical components like vertical-cavity surface-emitting laser (VCSELs), Silicon photonic or other optical chips, or Light emitting diodes (LEDs) to be interconnected with the corresponding receiving devices like PIN diodes, or a standardized optical output in an OCP, like proposed in figure 1.

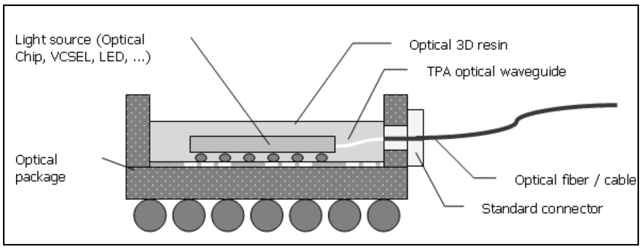

Figure 1 Representation of 3D waveguide connecting an optical component with an optical output, yielding an Optical Chip Module (OCM).

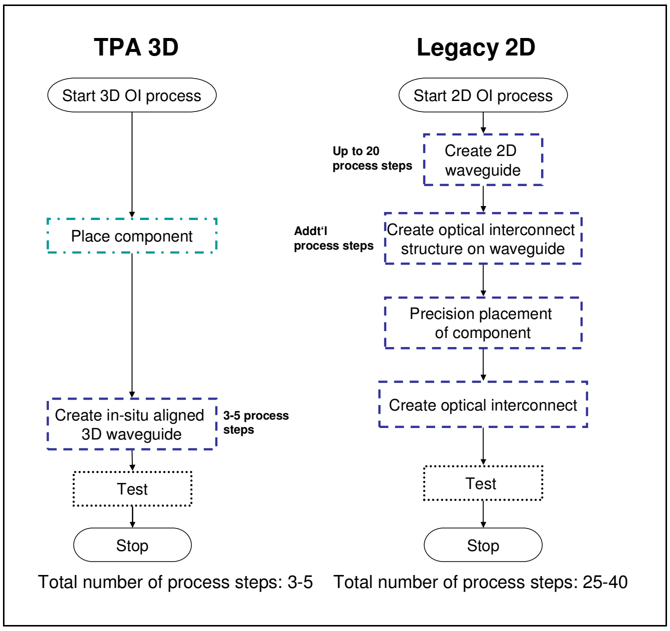

Figure 2 a) New 3D TPA laser lithography optical interconnects manufacturing process flow. b) Legacy 2D optical interconnects manufacturing process flow.

2.2 The 3D-waveguide manufacturing process

2.2.1 Introduction of 3D in optical interconnects

To achieve 3D optical connectivity, a 3-dimensional optical waveguide is created within an optical medium. The process flow for creating the 3D waveguides is outlined in Figure 2a. The advantage of the process flow is that the large number of process steps required for generating waveguide structures on planar substrates is significantly decreased, from up to 40 process steps to as little as 5 process steps. The proposed process sequence is significantly shorter; it requires less consumables and uses less energy. The most prominent feature of the technology is the capability of creating real 3-dimensional waveguide structures. There is no other known waveguide manufacturing process that readily allows 3-dimensional waveguides to be created, let alone in an upscale, affordable manufacturing environment.

One of the existing process flows for manufacturing an optical waveguide and interconnect is sketched in Figure 2b. The number of process steps alone hints towards a very complex manufacturing process chain, with the corresponding price tag. This process sequence and similar process sequences are described in the literature (see references 1-5 above on optical waveguide manufacturing).

The number of process steps for attaining 3D waveguides can in principle be reduced to a minimum of 3 individual steps, for practical reasons 5 process steps are needed in the current state-of-technology. These process steps are outlined below.

2.2.2 Step 1: Component assembly

As a first step the optical components are assembled on a substrate, carrier or circuit board. For an individual optical chip, the assembly could be done in a socket, where also the electrical interconnections are established (see figure 1). The socket is surrounded by a frame that is used for creating a defined volume that is used in step 2 for the confinement of the optical material.

The assembly process can be done using existing assembly equipment, with the process capability inherent to the equipment. Within wide limits, misalignment, process variation of the placement of individual components will be compensated for during the formation of the optical waveguide. This allows the assembly process to be carried out in a fast manner, as for electronic/electrical components.

2.2.3 Step 2: Introduction of optical material

In a second step, the optical material for creating the waveguide is applied to the assembly using dispensing, stencil printing or other deposition processes fitting the purpose. This material will later be the waveguide and the cladding material. It may also serve as glob top and/or underfill.

2.2.4 Step 3: Thermal cure

In an optional process step the waveguide material is subjected to a thermal curing operation where the material is fixed.

2.2.5 Step 4: Waveguide writing

At the core of the proposed process sequence, in step 4 the waveguides are written into the material using Two-Photon Absorption (TPA) lithography. As an intrinsic feature of this process, the waveguide structures are precisely aligned with the pre-assembled components, connecting their optical interface to the designated input or output location.

For attaining the location of the optical I/O, the position of the component in 3D space is measured precisely by optical analysis, determining x, y and z position as well as rotation and tilt using state-of-the-art vision systems. Using the component specification, the position of the optical I/O of the component is calculated. Both pieces of information combined specify the location where the optical waveguide writing needs to be started. In the example of figure 1, the output location of the standardized connector represents the other terminal of the optical waveguide. With the location of both end points of the optical I/O defined, the calculation of the waveguide is done in situ by geometrical optimization of the waveguide with respect to insertion loss. Pre-calculated optical waveguide segments may be also used and connected in this process to reduce process time. The TPA lithography process allows multiple waveguides to be created inside the material. The waveguides may be arranged in parallel; they may intersect, and may come in bundles to allow space multiplexing (see Figure 3 for an example). The waveguides may be created as a taper (in situ) to account for differences in mode field diameter of the optical I/O on either terminal of the waveguide.

2.2.6 Step 5: Final cure

As a final step, after the waveguide and interconnect structuring has been completed, the remaining material is cured to stabilize the waveguides inside the cladding matrix. The cured package is mechanically stable and carries optical interconnects that functionally connects the optical components with the package.

The described process has been shown to work in PCB manufacturing [9] with subsequent processing of the optical layer in a lamination press at 200°C. Current materials available maintain a refractive index difference Δn of 0.005 – 0.01, which is large enough for SM waveguides to adequately guide light [6].

2.3 Immediate advantages and future options

The main advantage of the proposed process sequence using TPA lithography is that the slower alignment process for creating the optical interconnect is separated from the fast, known and standardized assembly process. Taking advantage of established high-volume manufacturing processes and combining them with special processes required for optical components may lead the way to more efficient manufacturing of components and products with optical interconnects. The proposed process sequence thus differs quite dramatically from the traditional approaches, allowing new types of solutions to be created.

The process described above yields precisely aligned level 1 optical interconnects, that allow optical components to be easily integrated into an electronic assembly, using state-of-the-art process equipment.

In a similar process sequence, a level 1 optical interconnection between optical components on the same substrate seem feasible, allowing the creation of Optical Multi- Chip Modules (OMCM). These would feature multiple components on one substrate which could either have optical connectivity only within the package, or also with the next interconnect level.

3 Requirements and opportunities for real 3D optical interconnects

3.1 Optical interface design

In addition to simply writing a 3D waveguide structure with the TPA process, the interfaces between the waveguides and the optical I/O may be tailored in 3D to the specific interconnection challenge to maximize the coupling efficiency. Simple waveguide structures might consider the numerical aperture of the arrangement and allow the waveguide structure to be started with a standoff from the component. Refinement might be needed for adjusting the waveguide diameter to the mode field diameter of the components and the receiving optical fiber, thus requiring the use of in situ created tapers. While the optimization of the optical interconnection using the 3D waveguide structuring is possible, the considerations for optimizing the system design should be done in an early development stage. Figure 3 shows the positioning of perfectly circular waveguide facets. The waveguides were created using TPA polymerization. The image shows the fluorescence image of the cross section of the waveguide array. The optical power and writing speed for triggering the TPA polymerization process was varied to identify the potential for dynamically tuning the diameter of waveguides. The diameter was varied between approximately 3 to 8 micrometers by variation of laser power and writing speed.

Taking advantage of solutions featuring waveguide arrays, tapers in situ manufactured components will be key to creating optical component assemblies that exhibit better manufacturability along the whole value chain.

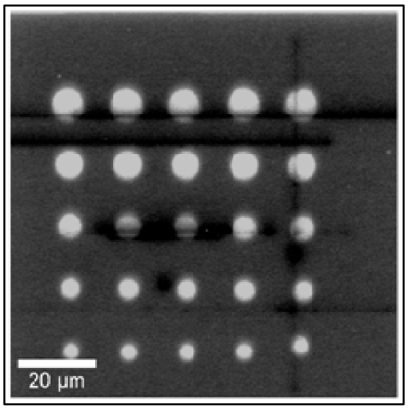

Figure 3: Fluorescence characterization of the facets of a waveguides array created by TPA lithography. [S. Steenhusen, S. Steenhusen, R. Houbertz], Courtesy of Fraunhofer ISC.

3.2 Material requirements

The TPA lithography process offers various opportunities for simplifying the creation of optical modules and devices. At the same time the process depends on the usage of materials that have very specific properties.

The optical component package shown in figure 1 poses a number of different requirements, which become relevant throughout the build-up process of the component. As the main feature of the new process, the material used for creation of the 3D structures is applied only once, and processed in two curing steps. There is no need for developing the non-cured material. As a process variation multiple materials may be used, which also allows the combination of TPA lithography with more standard methods [10]. The following set of general requirements towards the material is:

a) Polymerization of the material using the two-photon polymerization process has to be possible for attaining the desired 3D structures;

b) the non TPA-polymerized matrix material must be thermally curable so that the resulting refractive index Δn is different from the TPA polymerized material;

c) the Δn needs to be retained throughout the operational lifetime of the optical device;

d) a low material absorption is needed (< 0.1 dB/cm);

e) the material must withstand the processing conditions of the optoelectronic substrate and component manufacturing;

f) the material must withstand the specified operational conditions;

g) other desirable properties like low water uptake, CTE matching the optical chip material and the surrounding socket, or flexibility of the material.

Materials that suit most requirements have been under development and have been demonstrated to work in laboratory and demonstration arrangements [9].

4 Summary

A process for creating 3-dimensional waveguides is proposed that yields a significant reduction in process complexity and cost while offering a new way for creating optical component packages that can be scaled to high volume manufacturing.

5 Acknowledgements

We thank Sönke Steenhusen for his outstanding work in the TPA projects, and our partner Fraunhofer ISC for its promotion. Financial support of the German Science Foundation in the framework of its Priority Program SPP 1327 (grant: HO 2475/3-1) and our cooperation partners for fruitful cooperation is gratefully acknowledged.

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