Miniaturized Optical Data Link Assembly for 360 µm Guidewires

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***Abstract*— We propose a novel concept for a high-speed optical data link in Ø 360 µm cardiovascular interventional imaging guidewires. The concept is based on the recently introduced Flex-to-Rigid (F2R) technology platform. This technology allows for smaller intravascular imaging devices with a more compact form-factor. We extended the existing F2R technology with a new optical data link assembly method to enable high speed data communication from the distal tip of the catheter to the proximal side. In this method, the fiber is aligned by inserting it into a through-wafer hole directly underneath the flip-chipped Vertical-Cavity-Surface Emitting Laser (VCSEL). Therefore, the total diameter of the optical data link is primarily limited by the size of the VCSEL. A wafer-scale demonstration setup was fabricated with a commercially available 350x250 µm VCSEL and a Ø 80 µm multimode optical fiber. Test results of our demonstrator show a correct optic coupling of the VCSEL into the fiber.**

Keywords*— *optical coupling; data link; Flex-to-Rigid; guidewire; CMUT; micro assembly; minimally invasive instrument

I. Introduction

A. Background on Intravascular Ultrasound

Taking 7.25 million lives per year Coronary Artery Disease is (CAD) is the leading cause of death worldwide [1]. When suffering from CAD the coronary arteries are narrowed due to the accumulation of atheromatous plaques on the arterial walls. As a result less oxygen is transported to the heart muscles. Eventually this can cause chest pain and shortness of breath. Furthermore, it can lead to severe complications such as a stroke or cardiac arrest when part of the plaque breaks away. CAD has been identified as a complex inflammatory disorder linked to obesity, metabolic syndrome, and diabetes [2]. If diagnosed early, the risk of catastrophic failure can be decreased by a change of lifestyle or medication. But in case of severe stenosis surgery might become necessary. Often, the best surgical option available is a minimally invasive procedure called Percutaneous Coronary Intervention (PCI). In this procedure, first a flexible guidewire is inserted and a catheter is slid over it towards the stenosis (Fig. 1). At the tip of this catheter is a balloon which can be inflated to compress the plaque against the arterial wall. In some cases a mesh tubing (stent) is placed to prevent the artery from collapsing again.

Although PCI often has proven to be successful, the procedure would greatly benefit from improvements in the imaging methodology used during this type of surgery. The current standard imaging technique to diagnose the severity of a stenosis is angiography. This technique creates a 2-D projection of the coronary arteries based on X-ray fluoroscopy enhanced by a radio-opaque contrast agent. A disadvantage of this technique is that the size of a stenosis is difficult to estimate due to it having a complex 3-D geometry [3]. In addition to angiography, Intravascular Ultrasound (IVUS) catheters can be used to acquire a 3-D representation of the stenosis. These imaging catheters generate a radial cross-section of the coronary lumen, stenosis and arterial wall with the use of ultrasound. Furthermore, IVUS catheters can also be used to evaluate the correct placement of the stent [4]. The first commercially available IVUS devices used mechanical rotating single piezoelectric element transducers to acquire an image [5].

B. Motivation for an optical data link in a guidewire

There is a trend in miniaturization of IVUS catheters [6]. The first devices could not reach into the smallest arteries and most stenosed areas. Developments in microfabrication have made it possible to replace the single rotating element by a circular array of 64 fine-pitched elements [7]. Making use of this development, a state-of-the-art instrument currently available is the 3.5 F (Ø 1.16 mm) Eagle Eye Platinum (Volcano Corporation). In a more recent study, it has been shown that the element size and pitch can be decreased further by replacing the piezoelectric elements with capacitive micromachined ultrasonic transducers (CMUTs) [8]. Their advantage is that the element pitch is only limited by lithography. The next logical step is to implement IVUS on a guidewire, the instrument that is inserted prior to the catheter during PCI. A recent proposal introduces a phased CMUT array inside a Ø 360 guidewire [9].

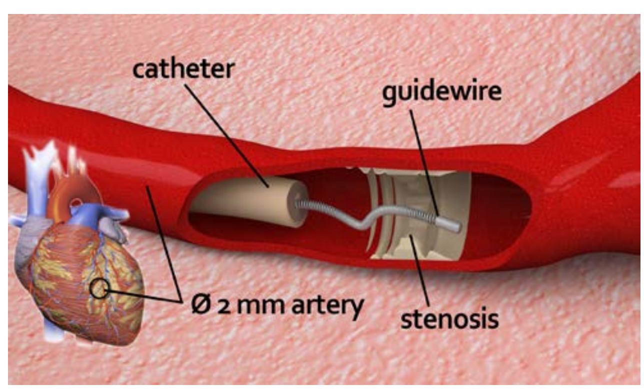

Fig. 1. During percutaneaus coronary intervention, a flexible guidewire is inserted in a coronary artery to guide the stiffer minimally invasive instruments such as catheters to the plaque location.

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Until now, the challenge of the data communication between the distal (at the heart) tip and the proximal (outside the patient) side for IVUS on a guidewire has not been addressed. To generate an image of sufficient resolution with a circular array inside a guidewire, at least 64 elements are required. Thus, a data connection with a bandwidth of at least 500 Mbit/s is necessary to transfer a stream of images to the proximal side of the guidewire. The first solution would be to use coaxial cables. But, a coaxial cable with well-defined characteristic impedance will be at least Ø 200 µm. However, usually a guidewire requires at its center a core wire with a distinct stiffness, often varying over the length. Together, a core wire and coaxial cable will not fit inside a Ø 360 µm guidewire. A second option would be to use smaller insulated wires which would fit next to the core wire. However, their bandwidth is not sufficient to communicate the IVUS images. Data compression could reduce the data size, but also here the limited space available does not allow the required complex calculations to be performed inside the guidewire.

The solution would be to move this problem from the electrical to the optical domain. We think an optical data link can be miniaturized enough to be used for IVUS on a guidewire. Currently, the smallest optical data link reported for this purpose fits within a catheter of 7 Fr. (Ø 2.33 mm) [10]. In our concept, a single Ø 80 µm multimode optical fiber is sufficient to communicate the data signal. Additionally, the optical fiber could probably replace the core wire as the stiffness is comparable. Developing a miniaturized optical data connection would also be the first step necessary to realize a MRI compatible IVUS device.

In this paper, we first introduce an IVUS on a guidewire concept with optical link. In Section III, we demonstrate the new assembly method of the optical data link required for this concept. We present the electrical measurements acquired from the optical link demonstrator sub-assembly in Section IV.

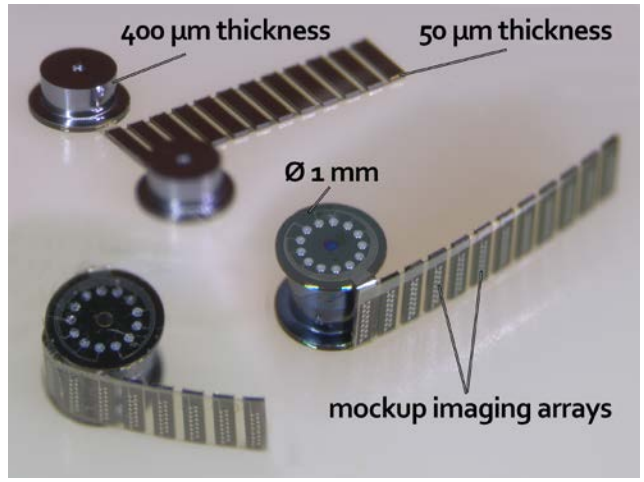
II. IVUS ON A GUIDEWIRE WITH OPTICAL LINK CONCEPT

The design of IVUS on a guidewire with an optical data link will have to meet several requirements. The total assembly for IVUS and an optical data link will have to fit within the 360 µm diameter of a guidewire. In addition to this challenge, the rigid part of the tip assembly should be shorter than 3 mm. Any longer rigid sections will not be able to fit through the sometimes tight corners of the arteries. Another requirement is that the complete assembly should be circle symmetric to prevent hysteresis at the distal tip when rotating the device at the proximal side. A uniform surface topography at the tip results in a more useful tactile feedback, which is an important feature for a guidewire.

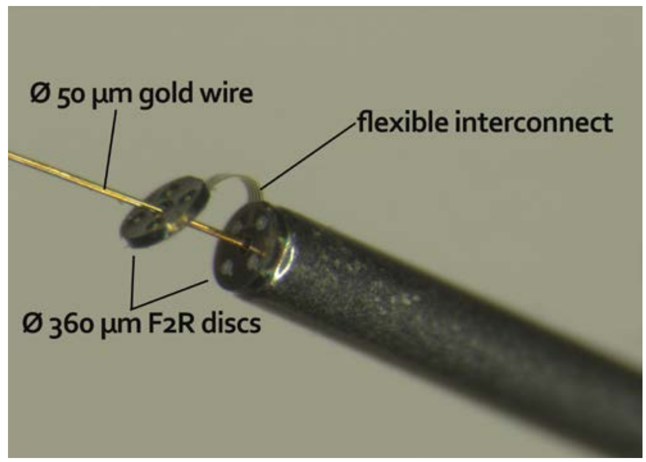
In the first part of this Section, the planar technology to fabricate a substrate that can meet the above requirements is introduced. In Sub-Section IIB the assembly concept and required components are explained.

A. F2R technological platform

To fabricate an assembly that fits the above mentioned size constraints, conventional manufacturing methods used for catheters are not suitable. As for the components themselves, an IC which has been diced by conventional means would make suboptimal use of the available cylindrical volume due to its rectangular prism shape. Furthermore, the components will need to be connected and a circular CMUT array would require many fine-pitched interconnects. Wirebonding or soldering these is not a cost-effective solution.



(a)



(b)

Fig. 2. Examples of several F2R based s. (a) A folded IVUS mockup made with F2R. The rigid islands are connected by flexible interconnects. (b) A F2R guidewire-sized structure mounted on a 360 µm hollow needle.

The Flex-to-Rigid (F2R) technology platform has been designed previously to overcome issues such as these[11]. F2R is a planar process technology where the resulting device can be folded or rolled up to fit the desired small form-factor. The rigid silicon islands can be designed to have several thicknesses, ranging from 10 µm to the full thickness of the wafer. These islands are interconnected with flexible hinges or bridges made from polyimide. The polyimide bridges include aluminum routing layers acting as electrical interconnects between the islands. This metal layer is sandwiched between polyimide layers in the stress neutral plane. Therefore, the normal stresses in the aluminum layer are close to zero and a small bending radius can be achieved without breaking the interconnects. A bending radius for the hinges up to a minimum of 50 µm has been demonstrated [12]. In Fig. 2 several examples can be seen of F2R structures.

We propose to use F2R as substrate for IVUS on a guidewire. Therefore, the generic fabrication process of F2R

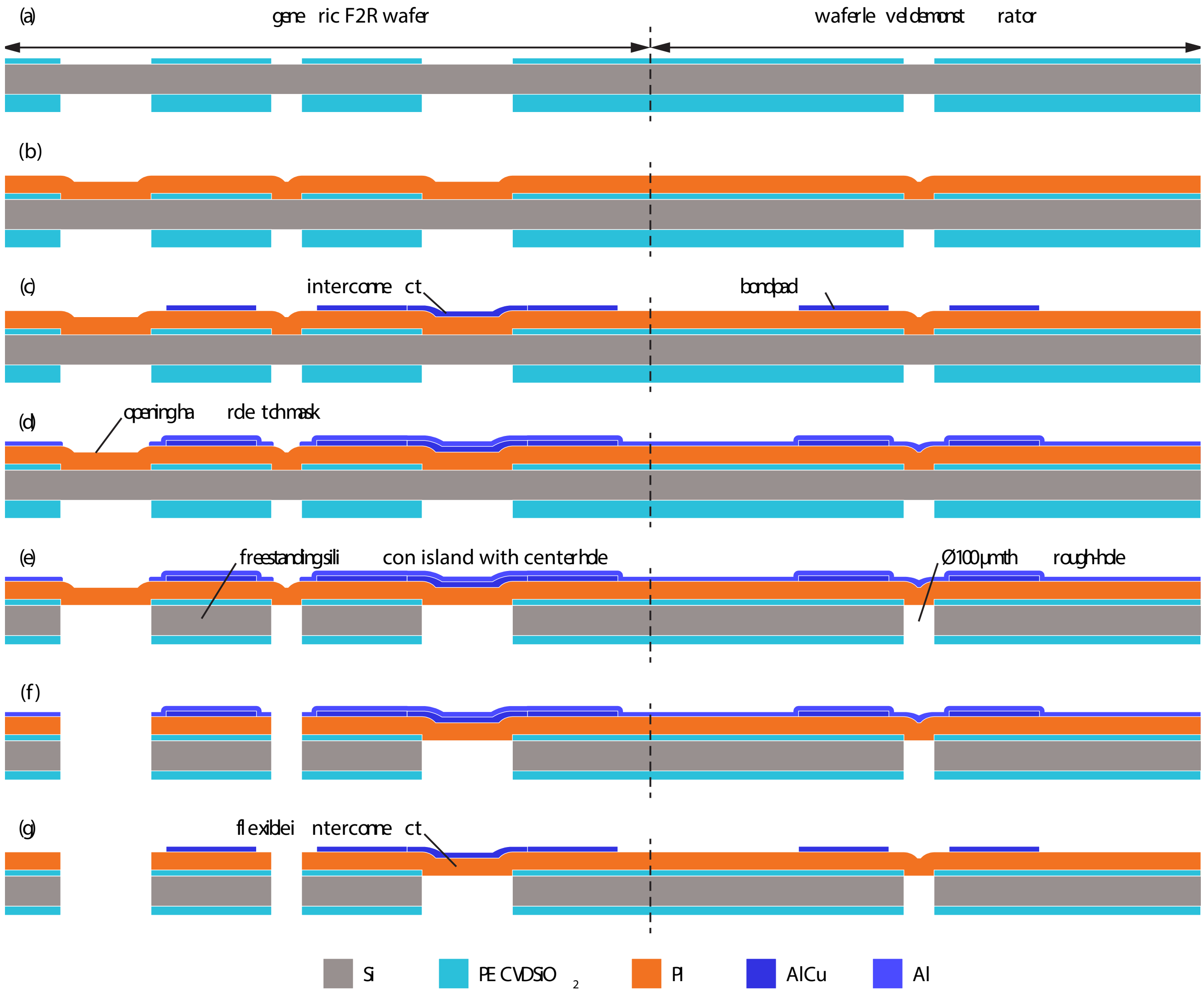


Fig. 3. The process flow for the generic fabrication process for F2R. The wafer level demonstrator used the same steps, but with a simplified mask design. (a) A PECVD SiO_2 layer is deposited on the front side (1 µm thick) and back side (5 µm thick) and patterned. (b) Polyimide is spun on the front side. (c) A 1 µm AlCu layer is deposited and patterned on the front side to form the bondpads and interconnects. (d) A hard etch mask for a later step is created by depositing a 200 nm Al layer and patterning it. (e) The backside is etched through the patterned SiO_2 with DRIE. Freestanding silicon islands are created, connected by the polyimide. (f) Most of the polyimide is dry etched around the island with the help of the hard etch mask. Only several polyimide bridges remain. (g) The hard etch mask is removed by wet etching with PES.

will be explained briefly. The fabrication process for the substrate used in the optical link demonstrator of Section III is based on the F2R process.

The fabrication has been performed in the Philips Innovation Services cleanroom in Eindhoven, The Netherlands. 150 mm P-type <100> 400 µm thick silicon wafers were used as starting material. As the first step in the fabrication process, a 1 µm low stress plasma enhanced chemical vapor deposition (PECVD) SiO_2 layer was deposited on the front side of a 400 µm silicon wafer (Fig. 3a). Another layer of 5 µm low stress PECVD SiO_2 was deposited on the back side. The front side was patterned using standard lithography on HPR504 resist, followed by a reactive ion etching (RIE) of the SiO_2 layer. The backside was processed in a similar way, but using a thicker layer of AZ4533 resist. A variation on the generic F2R process is possible at this point. By creating a two-step mask layer instead of a normal mask layer in the back side oxide, the rigid islands can be thinned to any desired thickness in a later fabrication step.

Next, VM651 primer was spun as an adhesion promoter for the adhesion of polyimide (PI) to silicon. PI2611 polyimide was then spin coated at a speed of 3000 rpm for 45 seconds, resulting in a 5 µm thick layer (Fig. 3b). The PI layer was cured for 3 hours at 350 °C in a high temperature inert gas (N_2) oven.

A 1 µm AlCu layer was deposited by sputter coating after a short sputter etch (Fig. 3c). The sputter etch was used to improve the adhesion of the AlCu to the PI. The metal layer was patterned with standard lithography by HPR504 resist and a subsequent wet etch by a phosphoric acid etchant (PES). In this step the AlCu bondpads and interconnects were created on top of the PI. Another 200 nm thick Al was sputtered on the front side (Fig. 3d). The layer was then patterned by repeating the process for the AlCu layer, but with another mask pattern.

In order to define the rigid islands and to create a through-hole for an optical fiber, the bulk silicon was etched using deep reactive ion etching (DRIE) on the back side (Fig. 3e). Here, the variation with the two-step SiO_2 mask can be implemented instead. For this variation, the silicon is first partially etched through the SiO_2 mask with DRIE. The larger windows in the SiO_2 mask are then opened by selective oxide ething with RIE. Next, a second DRIE completes the through silicon etch in the areas that had been etched before in the partial etch. The areas that were only exposed during the second DRIE will have been thinned down to their designed thickness. The wafer can now resume the standard fabrication process.

The next step is to pattern the PI layer using the hard etch mask and an O_2 plasma etch (Fig 3f). Most of the PI around the rigid islands is removed in this step. Only several thin bridges of PI remain, which are used to constrain the islands on the wafer. To complete the fabrication, the Al hard etch mask is removed with PES (Fig 3f). An example of a F2R processed wafer can be seen in Fig. 4. In order to release the devices from the wafer, the flexible bridges can either be cut by a laser or with a surgical scalpel.

In a variation of the F2R process, two PI layers of 2.5 µm each are spun instead of one thicker layer. During the process, the AlCu layer is sputtered and patterned between the two layers. Using this variation, the metal interconnects are more resistant against strain during bending as they are located in the neutral plane of the flexible bridges. The hard etch mask will be created on top of the second PI. The windows above the bondpads are opened when the hard etch mask is used to pattern the PI bridges.

B. *Concept and components*

It has been demonstrated previously that with the F2R technology annular arrays of transducer islands can be fabricated [11]. Although it will require further development of the technology, we consider it possible to use F2R to create a high-density array of 64 elements suitable for IVUS. A concept for IVUS on a guidewire is proposed based on high-density F2R (Fig. 5).

The device is powered with several insulated wires connected through the guidewire. These wires can also be used

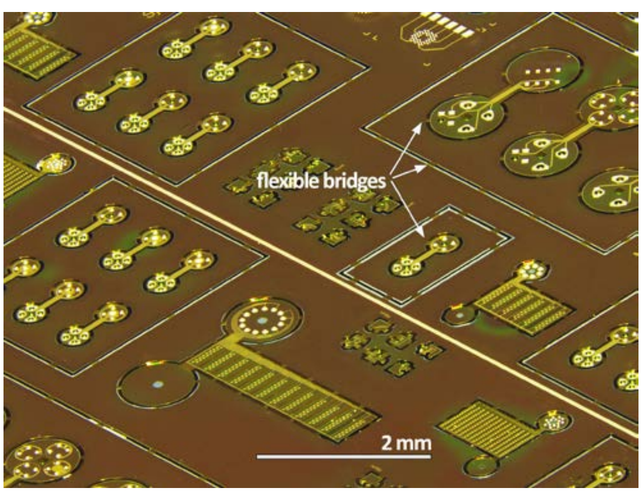


Fig. 4. An example of a F2R processed wafer. The devices are still fixed in the wafer by flexible PI bridges. A laser of surgical scalpel can be used to release them.

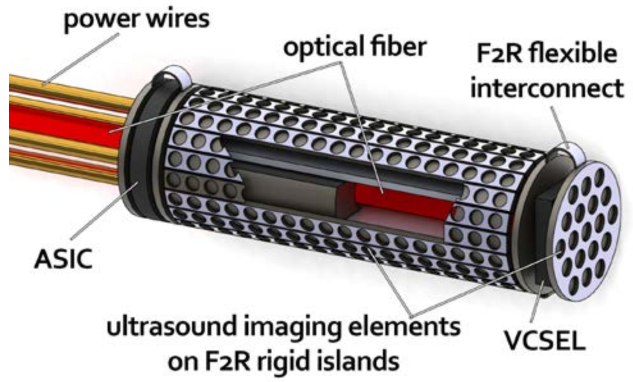


Fig. 5. A concept for IVUS on a 360 µm diameter guidewire with the required components. The optical fiber is used as guidewire core.

as control wires for the beam-steering of the CMUT array. Inside the guidewire assembly there is enough space for 8 insulated wires of Ø 50 µm. The annular CMUT array will provide side-looking IVUS. An optional forward-looking Ø 360 µm disc-shaped CMUT array could be used to evaluate chronic total occlusions. The array elements are connnected through the F2R flexible bridges to a control Application-Specific Integrated Circuit (ASIC). The torus-shaped ASIC distributes the power to the CMUTs and creates an output signal through multiplexing. Most likely the ASIC will require more space than available in a single island. In that case, the ASIC functionality could be split up among several ASICs, stacked like a sandwich. Alternatively, the space inside the cylinder of the annular array could be used to incorporate a larger rectangular ASIC. The multiplexed signal from the ASIC is converted into an optical signal by the Vertical-Cavity Surface-Emitting Laser (VCSEL). The optical signal is then coupled into an Ø 80 µm multi-mode optical fiber. To keep a high rotational symmetry in regard to the mechanical properties, the optical fiber is designed to be at the centerline of the guidewire.

As optical source for the data link we propose to use a VCSEL because of its size and ease of integration. The Ø 10 µm light-emitting surface of the VCSEL should be easily centered within 5 µm misalignment above a Ø 100 µm

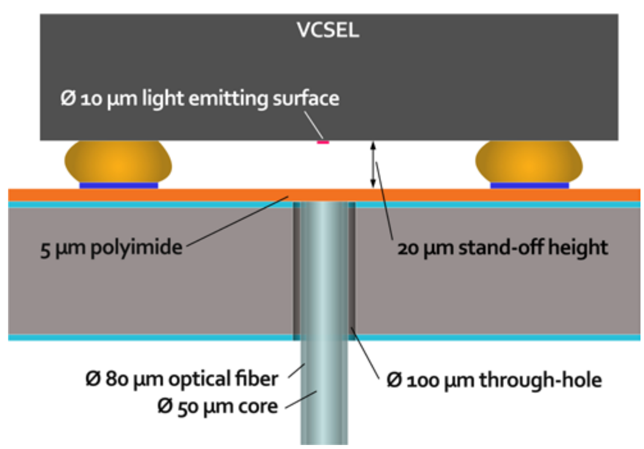


Fig. 6. Schematic cross-section of the alignment method. The VCSEL position is defined by solder self-alignment. The location of the hole is determined by lithography.

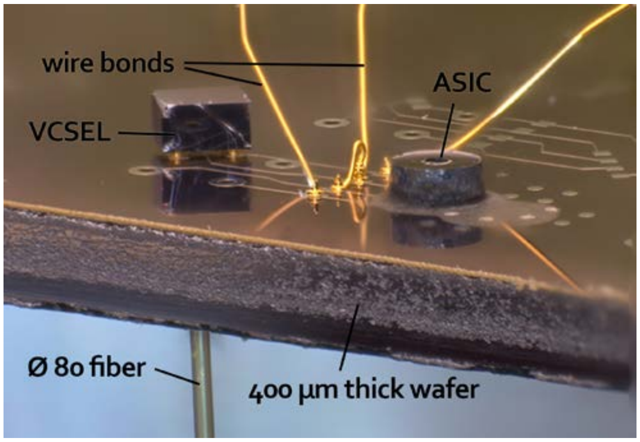


Fig. 7. Picture of the wafer-scale demonstrator. The VCSEL and ASIC were flipchipped on studbumps. Power to the ASIC was delivered through wire bonds.

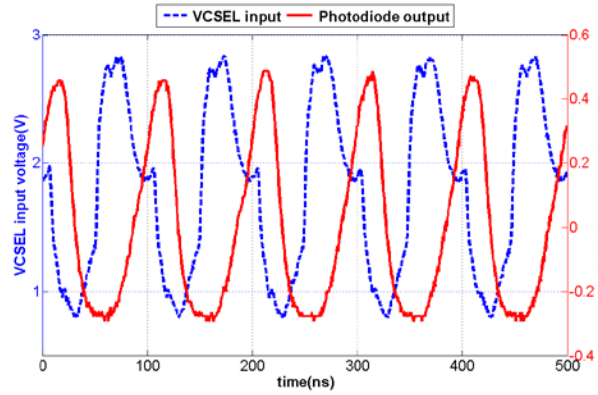


Fig. 8. Comparison of a signal communicated through the optical data link with the input signal generated by the ASIC. The frequencies match and an expected phase shift is observed.

through-hole containing the Ø 80 µm optical fiber (Fig. 6). As the distance between the distal tip and the proximal side should be relatively short a multi-mode fiber will be sufficient. An advantage of a multi-mode fiber over single-mode is that the core is much larger. Consequently, this allows for larger alignment errors.

Until now, has not yet been proven that this assembly method can be used to successfully couple the light from the VCSEL into the optical fiber. For that purpose, a sub-assembly of the optical link is fabricated and investigated in the next sections.

III. Fabrication of the Optical Link Demonstrator

For an optical link sub-assembly first a substrate needs to be fabricated based on a simplified F2R process flow. The process is exactly as described in section II-A, but using the structures from the right part of Fig 3. The design of this substrate does not contain any flexible hinges. Two variations of through-holes were made; with and without a PI cover.

The resulting wafer was diced and the dies were glued to PCBs for ease of handling. Gold studbumps were placed on top of the bondpads by ultrasonic welding. In the same process, gold wire bonds were placed between the substrate and the PCB. A commercially available 350x250 µm VCSEL (ULM850-10-FlipChip) and a custom designed oscillator ASIC were mounted on the studbumps with thermo-compressive bonding. The Ø 360 µm torus-shaped ASIC was available from an earlier experiment and served as a 10 Mbit/s laser driver. The frequency of the ASIC output signal depends on the differential voltage supplied. It was designed to deliver a maximum output frequency of 10 MHz at a 5 V bias.

The tip of the Ø 80 µm optical fiber was dipped in heat curing epoxy (EPO-TEK 353) before it was inserted in the through-hole. This was performed with the aid of a custom build assembly tool with xyz-stage. With the fiber inserted in the through-hole the epoxy was cured with the help of a heat gun. The resulting assembly can be seen in Fig. 7.

The device was tested in a custom made measurement setup. With the setup a differential voltage input was applied to the bondwires. The output signal from the ASIC was delivered to the anode of the VCSEL through the AlCu routing layer. The cathode is grounded through the bondwires connected to the PCB. The proximal side of the fiber was actively aligned to a 10 V reverse biased photodiode (Osram SFH203P). Both the signal from ASIC and the photodiode signal were monitored with an Agilent 54642D Oscilloscope.

IV. Results & Discussion

A demonstrator device with PI cover on the through-hole was tested. Alignment of the optical fiber proved easier with the help of the PI end-stop. Measurement results showed that the frequency from the photodiode matches with the input signal of the VCSEL (see Fig. 8). Both frequencies were measured to be 10.10 MHz. The ASIC was biased sub-optimally due to a routing error. Therefore, the rough oscillating signal from the ASIC as can be seen in the figure was expected. The routing error was caused by the fact that the layout of the ASIC bondpads did not correctly match the aluminium routing bondpads design. A solution was found in cross-wiring two of the input bondpads.

A signal delay of 50 ns is observed as expected due to parasitic capacitances. According to the data sheet of the photodiode a capacitance of 2.5 pF is expected. In addition, another capacitance was introduced in the cables connecting to the oscilloscope. The results confirms a successful optical coupling between the fiber and the VCSEL.

V. Conclusion

An IVUS on a guidewire concept based on F2R technology was introduced. For IVUS on a guidewire to be possible, the development of a high-speed data connection from the distal tip to the proximal side is required. We have proven a novel assembly method for a miniaturized optical data link by demonstrating a successful optical coupling. In this new method the diameter of the optical link is limited only by the size of the VCSEL. A 10 MHz oscillating signal was communicated through the first demonstrator of this optical link. With the results shown above we conclude the proposed optical link design to be a feasible method of assembly.

However, studbumping on the AlCu bondpads proved to be most challenging. As the bondpads were placed on top of an elastic PI layer, the energy from the ultrasonic bonding could not be transferred properly into the substrate. We found a very small sweet spot for the ultrasonic bonding settings that showed to work sometimes. In other cases either the studbump never fused to the bondpad or the bondpad was destroyed. In a next iteration, this problem can be solved easily by placing the bondpads directly on the substrate and adding a window in the PI layer above. Solder bumps can also be used instead of the studbumps. However, to enable solder bumping on F2R an improvement on the process will need to be investigated first.

More design improvements are to be considered. The 250x350 VCSEL used will not fit in a Ø 360 µm guidewire. The smaller 250x250 µm VCSEL (ULM850-14-CHIPS-V02) was developed recently by ULM and will be used in future implementations of the optical link. A custom designed 2.5 GBit/s VCSEL laser driver has also been developed to replace the 10 MHz oscillator. The next iteration of the optical link will be demonstrated on the concept based on the full F2R platform.

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