Electrical and Optical Micromachined Connectors, Clips and Clamps

Nuradawiyah Zaidon, Michael P. Larsson, Richard R. A. Syms and Stepan Lucyszyn

Abstract—**There are few good examples of micromachined electrical and optical connectors, clips and clamps reported in the open literature. For this reason, a review of such devices is presented. The mechanical properties of the structures and materials used are given, in order to understand the physical limits of the designs. Examples of analysis for such microstructures are also briefly discussed.**

Index Terms— **connectors, clips, clamps, silicon, silicon nitride, micromachining.**

I. INTRODUCTION

THERE is an ever-increasing demand for the design of electrical and optical components in telecommunications, for example, to have greater performance but with smaller scales of size and cost. Miniaturization has shown a trend towards the reduction in physical size that began with purely mechanical devices, then later with optical and most recently with electronic devices. Today, research has shown that the microelectronics, optics and micromachining fields can incorporate one another. Indeed, recent advances in micromachining can possibly offer miniaturized devices at lower cost.

Various electrical and optical micromachined connectors, clips, and clamps have been developed over the past few decades with the help of micromachining and microelectromechanical systems (MEMS) technologies.

It is useful at this point to introduce the underlying concepts of MEMS by first defining some common nomenclature. The term microsystems technology is generally used within Europe and this represents specific micromachined components (e.g. static-micromachined, self-assembled and vibrational), microelectromechanical systems (e.g. those actuated using electrostatic, piezoelectric, electromagnetic or electrothermal mechanisms) and microfluidic technologies. It can be stated without ambiguity that MEMS components are micromachined components, but not necessarily *vice versa*. Having said this, some non-MEMS micromaching technologies have been mislabelled as MEMS. Here, *microelectromechanical systems* relates to the following literal interpretation: *systems* corresponds to the integration of the functional (i.e. electrical or optical) component and its associated actuator; *mechanical* relates to both the physical displacement of and mechanical interaction between the functional component and its reconfigurable actuator; *electro* corresponds to the actuator's electrical bias that is independent of any functional signal; and *micro* corresponds to the micrometer-scale dimensional feature sizes of the functional component and/or its actuator.

Micromachined and MEMS technologies offer the potential for the fabrication of miniaturized mechanical devices that can be integrated within electrical and optical systems. Such technologies employ either *bulk* or *surface* micromachining; both can have many fabrication processes in common, such as photolithography, oxidation and etching.

In contrast to surface micromachining, bulk micromachining uses anisotropic etchants, anodic/fusion bonding, double-sided processing and electrochemical etching [1]. Here, the fabrication processing of a micromechanical structure can include orientation-dependent wet anisotropic etching of the silicon substrate [2]. This technology is useful for components that require moving elements that could have feature sizes of several 100 μm and lengths of up to 2 cm, yet may require alignment accuracies that are of the order of 1 μm [3].

With surface micromachining, a micromechanical structure relies on the use of sacrificial layers. A photolithographic process is required for each layer of sacrificial and structural material used, until a complete micromechanical device is realized. A final etching process is needed to remove the sacrificial material from within the device, in order to release the desired free-moving structures. With each reported demonstrator [4-6], micromachining is used to offer benefits to actuation power, size and/or cost of packaging /assembly.

With electrical connectors, higher levels of integration dictate greater pin densities and, thus, smaller devices. Section II will describe a separable connector technology that has been developed at Imperial College London. Two other microconnector examples are also given for different applications.

High-precision optical devices are vital to achieve greater coupling efficiencies. Therefore, with optical fibres, microclips are required to improved performance through better alignment and thermal stability. Silicon nitride microclips have been fabricated onto silicon

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N. Zaidon, M. P. Larsson, R. R. A. Syms and S. Lucyszyn are with the Optical and Semiconductor Devices Group, Department of Electrical and Electronic Engineering, Imperial College London, London, SW7 2AZ, U.K. (phone: + 44 (0)20 7594 6167; fax: + 44 (0)20 7594 6308; e-mail: stepan@ieee.org).

substrate V grooves. These clips are deflected by the fibre and act as springs to hold the fibre kinematically in place. The success of anisotropic etching of silicon [4] has shown that optical fibres can be accurately aligned within the V-shaped grooves.

A higher displacement range and holding force can be achieved with bi-stable microclamps.

This paper reviews the mechanical, optical and electrical design of connectors, clips and clamps, and gives examples of theoretical and simulation results for various micromechanical designs.

II. DESIGN CONCEPTS

A. *Connectors*

An electrical connector is required to provide a separable interface between two subunits, without adversely affecting the performance of the electronic system [5]. There are several types of electrical connectors, with different functions and designs that employ micromachining to reduce size [5].

1. Cable connectors are used to make a demountable connection between two cables. Connection is made in a direction parallel to the cable axis, by insertion of the male part into the female part and this is known as an *in-line* connector. While a *ribbon* connector is referred to as a connection that lies parallel in a plane.
2. Board connectors have two main types, *edge* connectors, for circuit board to cable connections, and *motherboard* connectors that connect one board to another.
3. Chip connectors, having a permanent solder connection, connect integrated circuits to miniature boards within a multichip module (MCM) assembly.
4. Probe testers create a temporary connection during the quality inspection stage of integrated circuit manufacture.

Research at Imperial College London, demonstrated an improved *in-line* separable connector that has a sliding connection between male and female halves [5], by introducing vertical deflections in a set of flexible conductors. This design successfully establishes stable electrical contacts having a 250 μm pitch. Rails and trenches are formed by an anisotropic etching process. Alignment rails on the female part and trenches within the male part are used to maintain precise alignment between both sets of conductors. The female parts of the connectors were designed to have a series of conductor lengths and the male trench widths were also varied to allow for variations in the contact force. The fabrication of the connector prototype consists of a three-mask process. Conductors are made of 20 μm thick nickel, as the structural material, and plated with 2 μm thick gold. Male and female connector components, as shown in Fig. 1, were fabricated on a common substrate before separating into dies.

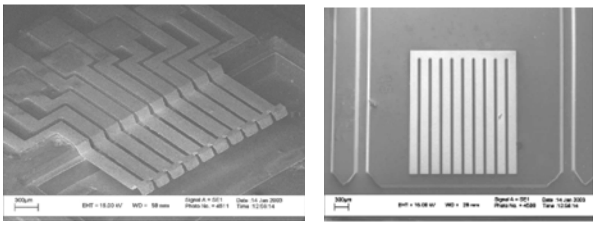

(a) (b)

Fig. 1. Connector components [5]: (a) female; and (b) male

Later, Larsson *et al.* carried out research that demonstrated micromachined separable radio frequency (RF) connectors, using low-resistivity silicon (LRS) as the substrate material [6]. At high frequencies, electrical connectors can acts as transmission lines, since the connector dimensions can coincide with the guided wavelength of transmitted signal. As a result, the physical dimensions need to be designed according to the characteristic impedance of the transmission lines to which they are connected. This high frequency connector is fabricated in silicon. It contains features of self-alignment and pins capable of out-of-plane deflections, on top of the basic embodiment of the dc connectors [5]. For RF operation, modifications of the pin arrangement were undertaken to remove the reliance on electroplated Ni as the structural layer. Here, SU-8 dielectric is used to reduce lossy substrate coupling. In addition, to ensure a robust attachment to the substrate during fabrication and in service, mechanical interlocking is added to the design.

Another type of microconnector, developed in Japan [7], combines electrical and mechanical elements and is used in a chain-type of micromachined system (as part of the Ministry of International Trade and Industry (MITI) – Industrial Science and Technology Frontier Program). The system detects flaws in a tube by vertical movement. Each device has a pair of microconnectors, with dimensions of 5 x 5 x 5 mm^3, and the whole systems of ten microconnectors are connected together to encircle a 1-inch diameter tube. Each microconnector, having a diameter of only 2.5 mm and length of 2 mm, as seen in Fig. 2, comes with an automatic connecting/ disconnecting mechanism produced by a magnetic force. Automatic connection/disconnection was tested, with a connectable distance between opposing microconnectors of approximately 550 μm. The main part of the design uses a driving actuator to implement the automatic connection/disconnection action. The driving actuator consists of columnar permanent magnet, electromagnet and spiral spring. The permanent magnet is used to align a pair of microconnectors during mating. A pulsed current excites the electromagnet to create a repulsive force between the electromagnet and the permanent magnet, as a means of disconnection.

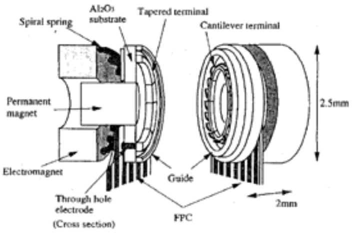


Fig. 2. Schematic configuration of microconnectors [7]

Micromachined connectors can be used in electronic packaging. The University of Colorado demonstrated connectors that are inserted beneath flip-chips [8]. The connector consists of a bimorph (polysilicon/gold) beam that deforms after heat treatment. The device chip will be in contact with the beam because of residual stress in the beam. Using an additional polysilicon electrode, the beam can be electrostatically-actuated to break the connection.

B. *Clips*

Two examples of microclips are discussed below, with a focus on their design concepts and applications.

1) Silicon microclips for SMD prototyping circuit

Ongoing research at Imperial College London is aimed at developing metal-plated silicon microclips to hold standard 0402 surface mounted device (SMD) components, having nominal dimensions of 0.5 x 0.5 x 1.0 mm^3, without any need for a conventional substrate. This unique interconnect technology offers the benefits of having zero substrate losses or parasitic detuning. As a result, the unloaded Q-factors associated with the lumped-element SMD components can be largely preserved when integrated into circuits. Planar microclips are located on a 525 µm deep nodal platform, to create +- and/or X-shaped structures; giving maximum flexibility when choosing the optimal circuit topology. Generic + and X /+ designs are illustrated in Fig. 3. Simplified nodal structures can also be made available in each configuration, with unnecessary microclips being removed, to minimize unwanted parasitic capacitances from the SMD components [9]. In addition, at the centre of the nodal platform, there is a square hole; for circuits to be constructed with orthogonal 3D architectures.

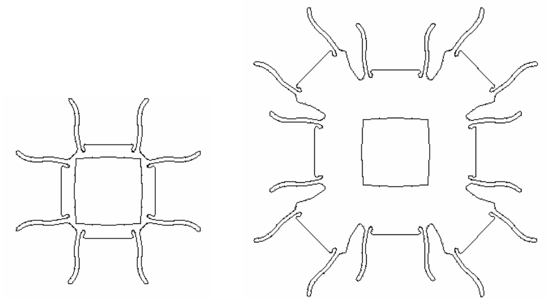

(a) (b)

Fig. 3. Plan view of two nodal structure designs: (a) +-shaped (peripheral *xyz*-dimensions of 1.4 x 1.4 x 0.5 mm^3); and (b) X /+ -shaped (peripheral *xyz*-dimensions of 2.18 x 2.18 x 0.5 mm^3)

Fig. 4 illustrates an orthogonal 3D architecture for a 2.4 GHz 3-pole band-pass filter embedded between standard SMA connectors. With this design, all the SMD components are mounted in the horizontal plane. In addition, metal-plated micromachined silicon ground rails have been introduced, and these are located below the SMD component layer. Moreover, special vertically oriented microclips have been designed to interface between the nodal structures, ground rails and SMA connectors.

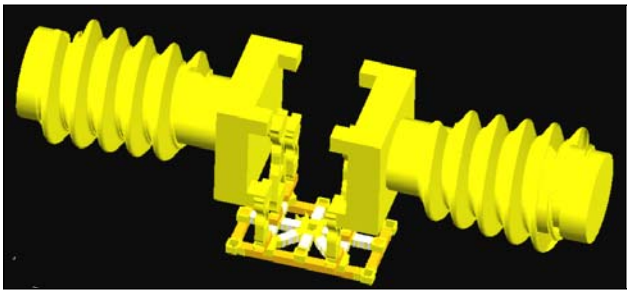


Fig. 4. AutoCAD design example of an orthogonal 3D architecture for a 2.4 GHz band-pass filter

2) Micromechanical clips for optical fibres

Precise alignment of optical fibres is very important, in order to reduce coupling losses within optoelectronic microsystems. Traditionally, fibres are attached by either gluing or welding metal-coated fibres into metal-coated V grooves. Precautions are required to eliminate damage due to glue wicking. Even though welding is much cleaner and gives more stable result than gluing, it requires metallization steps that increase cost.

Recently, microclips have been introduced as a better means of fibre attachment, when compared to gluing or welding. Here, flexible silicon nitride microclips were designed to hold single mode optical fibres in V-shaped grooves within silicon substrates [10]. A similar concept for clip design was first introduced in Sweden, using single crystal silicon [11]. It was later found that the clips had inferior stiffness and strength, when compared to those made from silicon nitride. Also, there are restrictions on available geometries and are more expensive to make [12]. Despite silicon nitride giving better performance than silicon, it is even more desirable for cantilever clips to be made from an even stiffer and stronger material (e.g. synthetic diamond).

Fibre-clips offer considerable benefits, as it is possible to repeat the fibre connection and disconnection. Bostock *et al.* conducted experiments that showed a fibre being successfully inserted into and taken out of one V groove 2000 times, at a speed of up to 5 mm/s [10]. As shown in Fig 5, a U-shaped entry taper, leading to the V groove is included in the design, to simplify the assembly process, thus, giving relaxed angular tolerances for insertion.

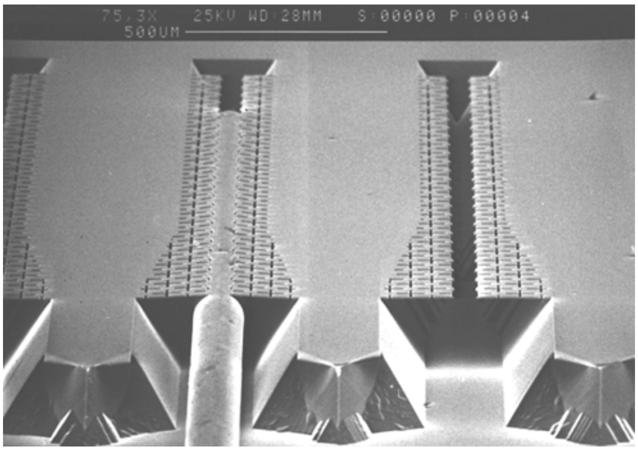


Fig. 5. Scanning electron micrograph (SEM) of the optical fibre held by silicon nitride clips in silicon V-shaped groove [10]

High-precision silicon micromachining is simple, using very few photolithographic steps. However, clip design is rather more challenging, when it comes to the geometry and dimension aspects. On one hand, the clip must be thin and sufficiently flexible, so that the fibre can be inserted and removed easily. On the other hand, the clips need to be thick and sufficiently stiff enough to exert a reliably large clipping force, to hold the fibres kinematically in place. In addition, the clips must be sufficiently strong enough to avoid them from breaking off from the silicon substrate and delamination along the film-substrate interface. Breaking off and delamination are mainly due to the stress concentrations at the corner between the groove edge and the clip. An effective optimization procedure, called *metamorphic development* (MD) is used to study the optimal thickness, mass and shape of the clips [13]. A combination of using this procedure with finite element computational methods aims to find the structural shapes and topologies of the microclips that minimize their structural compliance and weight, due to stress and deflection constraints.

C. *Clamps*

The bistable mechanism associated with clamps relates to two stable equilibrium positions within its range of motion [14]. The mechanism is at an equilibrium position when no external forces are required to maintain its position. Each bistable mechanism ideally stores and releases energy during motion.

For example, Boyle *et al.* [15] demonstrated a bistable clamp with lock and release mechanisms. These high-aspect ratio and large contact area clamps are used to locate and electrically lock/unlock optical components, with a wide tolerance range, at high forces. It was recorded that the clamps have locking ranges of up to 400 μm and calculated holding forces of the order of 25 mN. In addition, these clamps are a suitable candidate for optical assembly applications.

With reference to Fig. 6, in its initial stable (unlocked) state, the clamp changes to its second stable (locked) state, when voltage V1 is applied to its bent beam electrothermal actuator. The clamp remains in the locked state when V1 is removed. However, if V2 is now applied to the side springs, the outward motion of the bent beam electrothermal actuators enables the clamp to snap back. The motion of the bent beam changes the energy profiles to the extent that there becomes only one stable state that exists, which is the pre-clamp state.

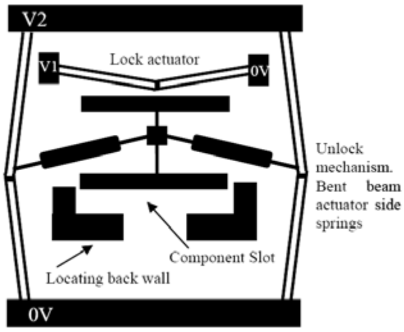


Fig. 6. Illustration of a bistable clamp [15]

With these clamps, the main design variable is clamp length, which dictates its snap-through range. Other important variables are angle of incline and side-spring rigidity, used to control the holding forces. The clamps are fabricated using deep reactive ion etching (DRIE) with bonded silicon on insulator (BSOI) wafers. Ideally, the gap between the actuator and clamp should be small. However, constrains on DRIE require a relatively large gap to ensure complete etching.

Another good example of a clamp design is found as part of an optical fibre switch [16]. This new bistable moving-fibre switch is fabricated using advanced silicon bulk micromachining. Bistable operation is favourable for long-term stability and low power consumption. The switches are based on a silicon device consisting of two main parts. The clamp adjusts the movable fibre in front of fixed fibres for bistable operation and an actuator is required for the movement between the switching states.

The complete mechanical design, including the actuators, was fabricated using only three mask levels. The mechanical structures are etched into <100> silicon wafers using anisotropic wet etching in KOH. Results obtained from the first switch prototype show good optical and mechanical performance. Insertion losses below 1 dB and crosstalk levels below -60 dB were achieved. After more than 15,000 switching cycles no degradation was found with the prototype [16]

III. DESIGN CHARACTERIZATION

Generally, it is important to understand both the mechanical and optical/electrical behaviour of the micromechanical design. Key physical parameters and the mechanical limits of the design and materials used are further discussed in this section. In addition, optical/electrical performances are also included.

A. *Connectors*

For the RF separable microconnectors, by Larsson *et al.* [6], a range of permissible effective pin lengths was determined, for various dielectric and silicon cantilever thickness combinations,. This is to ensure that maximum bending stresses are below the tensile failure stress for both dielectric and silicon. Inevitable stress concentrations at the base of each pin would raise local stress levels, reducing the nominal failure stress level for silicon during deflection [6].

Here, the multilayer pin structure consists of different physical properties of material used, requiring additional attention in mechanical design and electrical characteristics [6]. Fig. 7 shows the layer structures for each material used in both the dc and RF connector pins. With the dc connectors, each conductor is a quad-metallic strip, consisting of nickel (Ni) on a chromium-copper (Cr-Cu) seed layer, with a thin surface layer of gold (Au). The 20 μm thick Ni layer acts as the structural material and the 2 μm thick surface layer of gold is used to reduce the contact resistance. Ni is not suitable in RF applications below 10 GHz, because it can exhibit a high magnetic permeability [17].

As indicated in Fig. 7, for the RF connector pins, silicon is used as the structural material, but separated from the conductor by a thick layer of SU-8. The use of such a polymer dielectric has several advantages. First, the dielectric is located between the lossy LRS substrate and conductors, to help reduce parasitic coupling. Second, as the silicon substrate is now beneath the pins, the dielectric can be applied continuously throughout the connector structure. As a result, problems associated with impedance mismatching can be avoided.

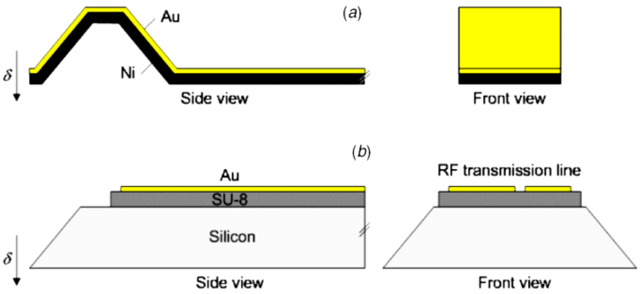


Fig. 7. Connector pin layer arrangement [6] for: (a) dc; and (b) RF

While the interfacial strength between SU-8 and the silicon cantilever support is important to the pin reliability during mating, delamination can occur, damaging the transmission line structure when there is insufficient support to sustain the shear stress during contact deflections.

B. *Clips*

With the flexible microclips by Bostock *et al.* [10], the ideal design represents a compromise between thickness, length and clip pattern. The clip thickness is a variable parameter that can be optimized to provide the required clipping force to kinematically locate the fibre within a V groove. In addition, the clip also needs to be sufficiently flexible so that the fibre can be inserted and removed with ease. For each thickness of clip, there is an ultimate deflection at which the clip will break, because of stress in the clip, due to bending at the attachment to the substrate. Deflection is inversely proportional to the clip thickness. This stress is either the ultimate tensile strength, or the stress for which a crack (due to surface roughness) propagates in the beam.

The clip length should also be design accurately, since it may affect the bending moment acting on the base of the cantilever. By using silicon nitride clips that are 88.5 µm long and 2 to 3 µm thick, with a designed tip deflection of 5 µm, it is shown that a holding force of 10 N/m is achievable [4].

The clip pattern can be altered to change the mechanical properties of the clips, to withstand the transverse shear force during fibre insertion or removal [10], or the form of the V groove in the taper. The pattern of the clip must be continuous, such that the fibre lifts the part of the clip ahead of itself during insertion. Stradman and Bäcklund [18] came up with a triangular clip pattern for silicon microclips, as seen in Fig. 8. These triangular clips are symmetrical and broad, with their strongest points being at the base from where they are attached to the groove edges. Furthermore, the fibres could be removed the same way as they were inserted without breaking the clips.

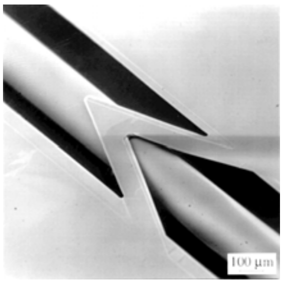


Fig. 8. Optical fibre fixed in a groove by triangular clip [18]

IV. DESIGN ANALYSIS

In order to optimize the performance of the assembly system, analytic calculations and/or computer simulations must be used to achieve both optimal mechanical and electrical/optical performance in the microstructure design. Each analysis must consider the worst-case scenario in every aspect that can contribute to a failure.

Thin films that are deposited on a bulk substrate are generally highly stressed [12]. Therefore, it is important to control residual stress and variations of stress with thickness during fabrication. In addition, a homogeneous stress causes a released microstructure to expand (compressive stress) or contract (tensile stress) [19]. The former should be avoided, since the structure may buckle under the compressive force. With the latter, the film gives rise to a tensile force in the structure that acts to stiffen the structure against movement. In order to avoid stresses within micromachined connectors, clips and clamps, it is vital to analyse the geometry with accurate data for material properties.

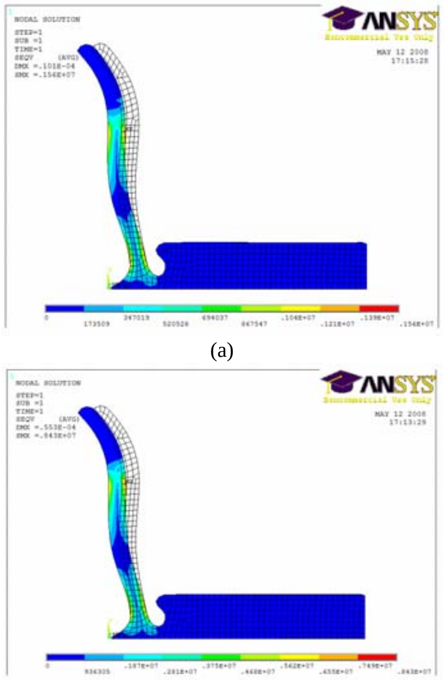
A. *Connectors*

High-frequency simulations were performed by Larsson *et al*. [6], to obtain loss predictions using the 3D electromagnetic field solver *HFSS*^{TM}. Here, models of a mated connector were created using two alternative dielectrics (SU-8 and BCB), with each having different thicknesses. A 38% reduction in insertion loss was observed from simulations with BCB having a thickness of 25 µm. A similar effect can be obtained by increasing the SU-8 layer thickness to 50 µm. Therefore, from these results, the insertion loss can be reduced by increasing the dielectric thickness or by using a dielectric material with a lower loss tangent (e.g. BCB). These two examples highlight the importance of simulations for achieving optimum geometry and choice of materials in a design.

B. *Clips*

Several simulation packages are available for the mechanical, electrical and optical design. In order to predict the stress levels for the silicon SMD microclips, ANSYS was used to investigate the stresses resulting from the forced bending conditions that are likely to be experience by the microclips during assembly.

Here, standard values of Young's modulus and Poisson's ratio for silicon were used in mechanical modelling. Young's modulus of the material and the ultimate stress are used to determine the maximum level of stress that can be sustained by the design. Contour plots from the simulated results for the microclip prototype design are shown in Fig. 9. Note that only one side of the clip needs to be investigated, due to the inherent symmetry. Simulated stresses are indicated by different colours, at maximum displacements for the extreme component widths of 450 µm and 550 µm.



(a)

(b)

Fig. 9. Microclip stresses at peak displacements for ±50 µm SMD width tolerances: (a) 450 µm (maximum stress is 1.56 GPa); and (b) 550 µm (maximum stress is 8.43 GPa)

V. CONCLUSIONS

An overview of the basic design concepts for connector, clip and clamp microstructures has been given. Separable RF connectors have been designed to operate at high frequencies, while using low-resistivity silicon as the substrate material.

Optimization of geometrical shapes and material properties in a design were highlighted as important factors for minimising design failures, which can be caused by extreme stresses when bending is experienced with microclips.

When optical fibres are coupled together, a precise alignment is required between both ends and this can be achieved by using silicon and silicon nitride microclips; this ensures low signal coupling loss. These clips act as springs that hold the fibre kinematically in a V-shaped groove. The optical fibre microclips can potentially be applied to several optical applications. One example is for fibre Fabry-Perot devices, which are compatible with optical fibre systems. Another application is an optical processor that can be used as a sensor for measuring distance. The clips help to increase the accuracy of mechanical movement that is being optically sensed.

Clamps with bistable mechanisms gain better stability performance. Such clamps have been fabricated with high aspect ratios and large contact areas, to produce large displacements and high holding forces.

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