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A Surface Mount Coaxial Connector for RF/Microwave Applications

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Abstract

The RF/microwave packaging and interconnect industry is now a $1.2 billion a year market. With the progression of ball grid array, flip-chip and surface mount technologies into the microwave and mm-wave domains, a need has evolved for coaxial connectors that attach directly to planar substrates. Coaxial cables are used to route high frequency signals between circuit modules in instruments and systems by providing a radially symmetric transmission structure for the signals. However, the structure within the modules is inherently planar and providing a transition between the radially symmetric and planar environments, particularly in higher frequency bands, is a formidable technical challenge. The difficulty arises predominantly from the fact that discontinuities at the interface cause impedance mismatches that degrade the electrical performance of the system. This paper introduces a glass-to-metal seal based coaxial connector that can be attached directly to the planar substrate of a circuit module or printed circuit board, enabling the circuit module to have a relatively smaller size and lower manufacturing cost. A case study will be presented to define an area of application for this connector technology and to demonstrate its utility.

Introduction

The global electronics industry, which encompasses computers, business equipment, consumer, military and automotive electronics, has experienced remarkable growth in the last decade of the 20th century and is now in excess of $1T a year [1]. The RF/microwave industry, including test equipment, radar and wireless telecommunications is estimated to be over $100B a year [2]. Although the packaging market segment of the RF/microwave industry, defined as IC packages, printed circuit boards, solder joining, wire bonding, cabling and connectors, represents less than 1% of the overall global electronics packaging industry, it is conservatively estimated to be over $1.2B a year [3]. By now it will be appreciated that the concept of guided electromagnetic wave propagation, demonstrated by the reclusive genius Oliver Heaviside over 100 years ago [4], has evolved into a massive multi-national business enterprise which at the beginning of the 21st century, provides the basis for a new world economy.

Mass production of electronic equipment can be traced back to the Second World War with the hand soldering of discrete components and rather primitive circuit boards for radar applications [5]. In the 1950's, wave solder technology for through-hole components enabled high-volume production of printed circuit boards [6]. This technology has proven to be the backbone of the electronics industry for almost fifty years. However, in the 1980's the advent of machine vision and pattern recognition fostered use of automated surface mount technology (SMT), resulting in dramatic densification of electronic assemblies [7]. Initially, surface mount components were peripherally leaded packages with a limited maximum lead count. But in the early 1990's pressure to increase interconnect densities led to the development of ball grid array (BGA) packages [8]. Although BGA technology is less expensive, thinner, lighter and more easily integrated into circuit board architectures than conventional hybrid microwave integrated circuit packages, issues with shielding, isolation and interconnection serve as drawbacks for RF/microwave subsystem applications.

In the mid-1990's the evolution of flip-chip technology (FCT) overcame some of the limitations of BGA for higher frequency applications and improved on interconnect density [9]. The advent of FCT was driven by digital applications such as high-end microprocessors, disk drive IC's, watches, and automotive ignition units. Consequently, flip-chip infrastructure has developed rapidly over the past five years. More recently, flip-chip device technology has been employed for applications in the mm-wave region such as automotive radar [10-12]. As the requirements for SMT, BGA and FCT based applications have moved to higher frequencies, the need for high performance coaxial connectors that interface directly to planar substrates has increased dramatically [13-21].

A Coaxial Connector for Planar Substrates

The primary method for routing high frequency signals between circuit modules in instruments and test systems is via semi-rigid coaxial cables. While coaxial cables provide a radially symmetric transmission structure for the signals, the transmission structures within the circuit modules are inherently planar. Generally, these structures incorporate microstrip transmission lines on a planar substrate. Due to requirements for signal isolation and low inductance, the electrical transition between the radially symmetric coaxial cable and planar microstrip environment is not only critical to the electrical performance of the system, but also technically challenging from both a design and manufacturing standpoint. This is particularly true for signals propagated in the microwave or millimeter wave frequency range where discontinuities at the transition interface cause impedance mismatches that can significantly degrade the electrical signal.

The traditional approach for minimizing discontinuities and impedance mismatches between coaxial and planar transmission structures for high frequency applications is to orient the center conductor of a coaxial connector assembly parallel to the plane of the circuit module's microstrip transmission line. This type of interface entails attaching the device substrate to the floor of a package body and then threading the connector assembly into a tapped hole in the wall of the package body. The position of the tapped hole aligns the center conductor with the planar transmission structure. Although this configuration results in favorable impedance matching at the interface, the fact that it relies on a package body increases the size and manufacturing cost of the circuit module. This paper presents a high performance glass-to-metal seal based coaxial connector which can be affixed directly to the planar substrate of a circuit module or printed circuit board [22], allowing the circuit module to be smaller and less expensive than conventional hybrid microcircuit package assemblies.

Figure 1 – Flanged coaxial connector.

In practice, the connector is attached directly to a planar substrate using solder or conductive epoxy. The substrate material can be ceramic, polymeric or a metal alloy, with suitable contact pads to foster the attachment process and assure electrical continuity. The connector is designed to mount perpendicular to the substrate and provide a transition between the circuit module and a semi-rigid cable. A cylindrical conductive bore, with a radially symmetric coaxial structure, is fabricated in the substrate to provide an impedance match between the coaxial and planar transmission structures. The mating surface of the connector is flanged to afford maximum contact area (see Figure 1). This insures electrical contact and enhances the mechanical stability of the assembly. A center pin protrudes through a hole in the flange, which has a nipple formed around it. The nipple serves to align the pin in the conductive bore of the substrate during the attachment process so that a symmetric coaxial transition is maintained. The circuit is completed with a suitable bond between the planar transmission line on the opposite side of the substrate and the end of the connector center pin extending through the substrate bore.

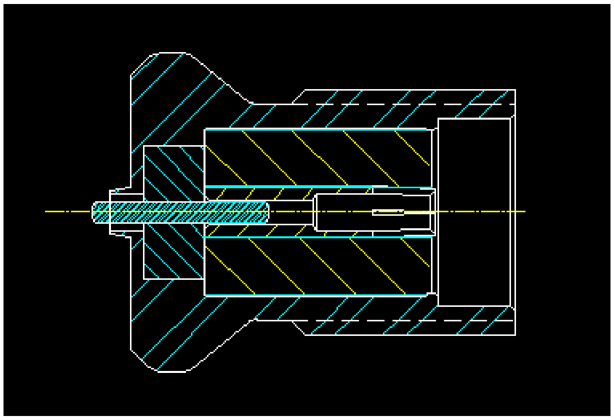

Figure 2 – Coaxial connector drawing.

Figure 2 shows an engineering drawing of the coaxial connector under consideration. The connector assembly is comprised of five lower level components: an outer conductor or housing, a glass bead, a center pin, a dielectric support bead, and a center conductor. Although surface mountable connectors do not generally require hermeticity, this connector features an integral glass-to-metal seal (discussed in the following section) to enhance mechanical stability and precisely locate the center pin in the housing through hole. The position of the center pin in the RF through hole is critical to the propagation of electrical signals as they exit the coaxial structure. The other end of the connector provides a transition to the external coaxial environment, in this case an SMA co-coplanar pin-and-socket style interface [23]. To accomplish that, the connector housing is threaded on the outside to receive a standard semi-rigid cable coupling. The center conductor is a slotted female contact with the end of the center conductor coincident with the mating plane of the connector housing. The center conductor is supported by a polytetrafluoroethylene (PTFE) dielectric bead, which is held in place via knurls on the outer diameter of the center conductor as well as notches on the inner diameter of the housing, just below the mating reference plane. The reliability of the mating interface geometry with respect to repeated connections is enhanced by the configuration described. This coaxial connector is designed and electrically compensated to function at frequencies in the 10 GHz range with exceptional electrical performance. It should be noted that this connector is not commercially available.

Principles of Glass-to-Metal Sealing

The distinct lack of thermodynamic affinity between glasses and metal alloys is the primary reason that joining of these materials has historically resulted in considerable technical complexity. The degree to which a liquid phase will wet a solid it is in physical contact with, within a vapor/liquid/solid three phase system, is a direct consequence of the particular conditions of thermodynamic equilibrium. By balancing the horizontal components of the interfacial energies (surface tensions) at the point of contact of such a three phase system (see Figure 3), Young [24] expressed this “mechanical” relationship at the turn of the last century in his now famous equation as (Eq. 1)

$$\gamma_{sv} - \gamma_{sl} = \gamma_{lv} \cos \theta \qquad (1)$$

where γ_{sv} is the interfacial energy between the solid and vapor, γ_{sl} is the interfacial energy between the solid and liquid, γ_{lv} is the interfacial energy between the liquid and vapor, and θ is the liquid/solid contact angle measured inside the sessile liquid drop. For the case depicted in Figure 3, $\gamma_{sv} > \gamma_{sl} > \gamma_{lv}$ so that the contact angle θ is acute, and by definition wetting of the solid by the liquid occurs. However, for the case where $\gamma_{sv} < \gamma_{sl} < \gamma_{lv}$, the contact angle is obtuse and wetting of the solid by the liquid is thermodynamically unfavorable. The second case is typical of liquid glass in contact with a metal alloy substrate.

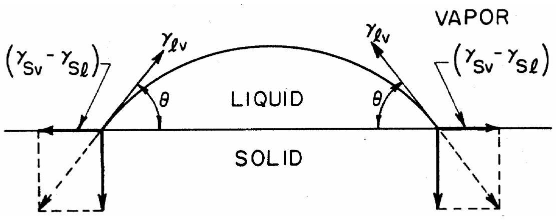

Figure 3 – Sessile drop configuration.
(Courtesy J.A. Pask and A.P. Tomsia)

Toward the end of the nineteenth century, Gibbs [25] presented a more rigorous thermodynamic treatment of Young’s construction. Although he accounted for the effects of a gravitational field on the system, like Young he assumed the system to be at chemical equilibrium with no mass transport across the interfaces. By now it is well established that the effect of chemical reactions on the relative interfacial energies of solid/liquid/vapor three phase systems, particularly at elevated temperatures where mass transfer effects can be significant, is such that the free energy of the reaction can enhance the driving force for wetting of the solid by the liquid [26]. This is true because mass transfer across the interfaces must result in a net decrease of the free energy of the system at any time, otherwise the reaction would not proceed.

The basic requirements for strong, hermetic glass-to-metal seals are chemical bonding (i.e. electronic structure via atomic contact) and minimal stress differentials at the interfaces with favorable stress gradients in the interfacial zones. It can be generalized that any two phases will form chemical bonds if they are at stable chemical thermodynamic equilibrium at their interface whether or not the bulk phases are at equilibrium, providing they are also compatible physically. Although it is well known that stress differentials at glass-to-metal seal (GMS) interfaces are minimized by matching the thermal expansion coefficients of the components [27], the dependence of stress gradients in the interfacial zones on composition gradients that form during the fusing of the seals is not as well recognized.

The technological procedure for achieving chemical bonding and favorable stress gradients in GMS assemblies is to first pre-oxidize the metallic alloy components. If the resulting metal oxide is of proper thickness and composition, when the GMS is fused at temperature the molten glass will wet and dissolve the oxide. The glass at the oxide interface immediately becomes saturated because the solution rate of the oxide is faster than the diffusion rate of the dissolved oxide into the bulk glass. In this way chemical bonding is realized. The oxide layer also bonds chemically to the metal, which is saturated with the oxide, at least at the metal/oxide interface.

As the dissolved oxide diffuses into the glass, a concentration gradient is formed that becomes more extended with time. The presence of the dissolved metal oxide in the molten glass affects its coefficient of thermal expansion because of an increase in the O/Si ratio and the introduction of cations with different degrees of covalency. The concentration gradients are then proportional to thermal expansion coefficient gradients, which generally results in more favorable stress gradients.

Hence, the saturation of the glass with metal oxide near the interface and the subsequent diffusion of the oxide into the bulk of the glass result in chemical bonding and favorable stress gradients as required. In effect, the metal oxide serves to act as a “thermodynamic glue.”

Case Study

The commercial state of the art for high-speed digital communication systems has now pushed beyond the previous 2.5 Gb/s to 10 Gb/s [28]. Recently, optical-fiber communication systems with a data rate of 40 Gb/s have been demonstrated [29]. The advent of dense wavelength division multiplexing (DWDM), with up to 128 wavelength channels co-propagating on a single fiber, has generated an aggregate communication bandwidth which exceeds the terabit per second level [30]. With these astonishing technological advances in bit rate and wavelength density, it is not surprising that the most important parameter for a digital communications system is the rate at which errors occur in the data bit stream. This figure of merit is a statistical parameter called the bit-error ratio (BER).

The Agilent 86130A BitAlyzer® is a 3.6 Gb/s general purpose BER tester designed for high-speed digital communication applications. The 86130A features excellent stimulus waveform shape and error detection technology that can rapidly record and analyze very long pseudo-random binary sequence (PRBS) data streams. This advanced BER tester is employed in design, manufacturing and quality assurance test environments to characterize the performance of photonic systems, components and fibers.

A BER tester consists of two primary sections: a pattern generator and an error detector. The pattern generator injects a known PRBS test pattern, along with a separate clock signal, into the system or component under test. This pattern is then received at the data input of the error detector where it is compared with an exact replica of the test pattern, which has been simultaneously generated by the detector logic. The error detector checks every received bit against its internally generated pattern and logs an error each time the received bit differs from the known transmitted bit. The pattern generator and the error detector must operate at identical clock rates and the phase relationship between them must be stable.

Figure 4 – Modified version of flanged coaxial connector.

The Agilent 86130A BER tester makes use of chip-on-board technology for its pattern generator and error detector modules. As such, a number of surface mount coaxial connectors are employed for both signal input and output functions to and from the modules. Figure 4 is a photograph showing both ends of the connector, which is a modified version of the coaxial connector described previously. The flange on this connector does not utilize a through hole, but rather the glass-to-metal seal interface is coincident with the flange surface. The coaxial mating interface is identical to the connector previously described. The photograph in Figure 5 shows three surface mount coaxial connectors in close proximity on the pattern generator module board. This connector design is very robust, mechanically and electrically, and is a key enabling factor for the high performance and reasonable manufacturing cost of the pattern generator and error detector modules for the 86130A.

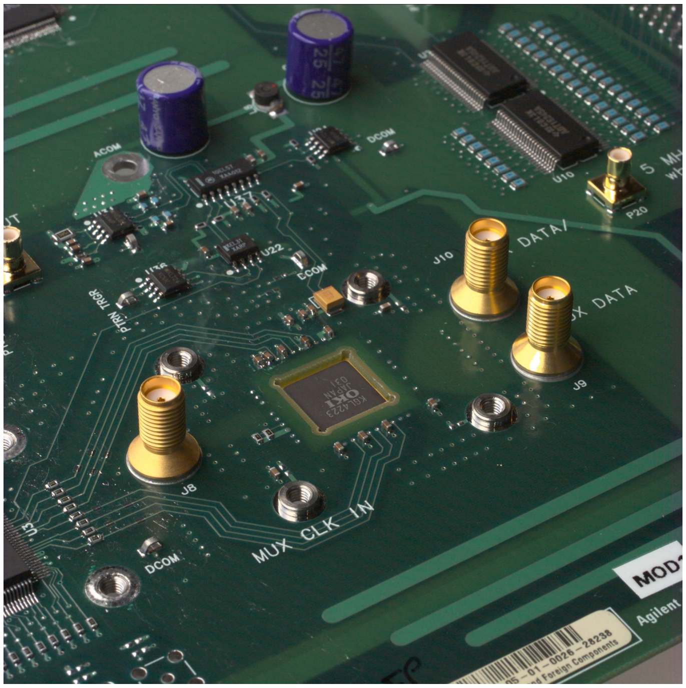

Figure 5 – Pattern generator module with connectors.

Conclusion

It is clear that advances in surface mount, ball grid array and flip-chip technologies are driving a need for high performance coaxial connectors that can be attached directly to planar substrates. A glass-to-metal seal based coaxial connector has been developed to satisfy the requirement for a surface mountable connector that provides a low inductance transition between radially symmetric and planar signal transmission structures at microwave and mm-wave frequencies. This connector is now effectively utilized in a new bit-error ratio test instrument for the digital communications market.

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