On the Design of Coplanar Bond Wires as Transmission Lines

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Abstract— **Bond wires are typically thought of as lumped electrical parasitic elements, and the usual design methodology is to make them as short as possible. Here, another scenario is shown where the bond wires may be thought of as transmission lines. Specifically, the practical system of "coplanar waveguide wires" is analyzed. If parameters are chosen carefully, especially with regard to wire height above substrate, they may impedance match the microstrip connector.**

WIRE-BONDING is the most widely used electrical packaging technique, but it becomes more problematic as data rates increase due to parasitics. The usual remedy for this is to reduce the wire length as much as possible to minimize the inductance of the wire. However, it is possible for bond wires to be transmission lines. Then, parasitics do not matter as long as the impedance of the wire is matched to the surrounding package, e.g., the microstrip substrate with which the device may be situated. Considered here is a package which consists of a device substrate (the chip) butted up against a microstrip substrate, so that the bond wire only traverses over the chip. It will be made clear that having large volumes of air around the wire, i.e., if there were a gap between the microstrip substrate and the chip, is highly undesirable. Not analyzed here, but considered part of the package, is a coaxial connector wedged over the signal line of the microstrip substrate. Note that the policy of not having large volumes of air surrounding the metallic lines also applies to the coaxial pin, meaning that the dielectric of the coaxial connector should butt up against the microstrip substrate. There has been some work evaluating bond wires as transmission lines [1]–[3]. There, a single wire situated above a substrate atop a ground plane was analyzed. However, a single wire arrangement is practically problematic since the substrate must be insulating for low microwave loss, and making electrical ground would require forming an electrical via through the substrate at the device position. For example, if the device under question is a laser and its substrate is insulating, both contacts to the laser are on the surface of the substrate and with a single wire a via must be formed.

The appropriate system is a coplanar arrangement (Fig. 1). Shown here is the fact that for coplanar wires to be a transmission line with constant impedance, their height above the substrate must be precisely maintained. This can be understood from the fact that the impedance of a transmission line is given by $Z_0 = Z_0'/(\varepsilon_{\text{eff}})^{1/2}$, where Z_0' is the impedance in air,

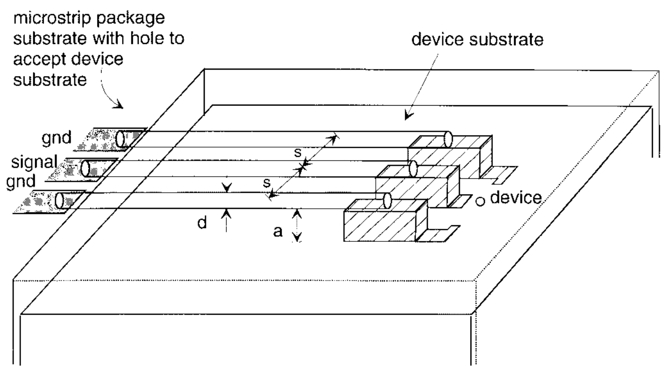

Fig. 1. Geometry of proposed package, which maintains constant height of coplanar waveguide wire bonding arrangement.

and ε_{eff} is the effective dielectric constant determined by how much of the microwave energy transmits through the substrate and how much in air. Shown here is that even with a small gap between the substrate and the wires, the field lines crowd in the gap, resulting in a rapid lowering of ε_{eff} and rise in impedance. It is for that reason that in the design of a microwave package, large volumes of air should never surround the metallic lines. In Fig. 1, it is proposed that the device substrate be recessed, and the device bond pads be thick, so that the wires are maintained at the same height as they traverse the device substrate. It is shown that an appropriate bond pad thickness is about a third of the wire diameter, or 8 μm for a 1-mil wire. Note that if the bond pads are 80 μm long and have a 50-μm spacing between them, this thickening of the bond pad contributes only 0.1 femtofarad of additional capacitance compared to thin bond pads. This "coplanar waveguide wire" transmission line is analyzed here and its impedance found as a function of the various parameters to allow design of this system.

Of course, one might argue that it is easier to place the bond pads at the very edge of the device substrate so that the wire length is small, either by designing the device at the very edge of the chip or by placing a microstrip line on the device substrate. This may be undesirable, for example, because damage from the chip dicing dictates that there be some guard space between the pads and the chip edge. What is provided here is simply another option in that the wire length can be kept long without deleterious effect.

The effective dielectric constant is found by taking the ratio of the capacitances of the transmission line cross section when the substrate's dielectric constant is its actual value and unity. In [1], analysis of the single wire system was performed

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using the usual conformal analysis. Using the same conformal transformation

$$w = u + jv = (z - jh)/(z + jh) \tag{1}$$

where $h = d/2 + a + b$, where d is the diameter of the wires, a is the spacing between the wires and the substrate, and b is the substrate thickness, it is straightforward to find that for a wire with a offset from the y axis of $s/2$, its transformed radius is given by

$$R = 2/[8h/d - d/(2h) + s^2/(2dh)] \tag{2}$$

and its transformed center position is given by

$$u = 1/[(4h)2/(s^2 - d^2) + 1] \tag{3}$$

$$v = s/[4h + s^2/(4h) - d^2/(4h)]. \tag{4}$$

However, given the increase in computing power available today, it is much simpler to calculate the effective dielectric constant of the system numerically [4]. In [4], the transmission of the wires as they traverse the device substrate is approximated by an average value. Indeed, in [4] the results are dominated by the choice of model which consists of an interconnection between two chips which are separated laterally, so that there is a large section of the wires that traverses a region with no substrate and a large gap above the ground plane. Here, as shown in Fig. 1, we are considering a very high-performance package which has no gap between the device chip and the microstrip package. Therefore the electrical properties are dominated by the wires as they traverse the device substrate. As stated above, it is proposed here that the wires be maintained at a constant height above the device substrate so that the impedance is constant along the wires. It is proposed that that be accomplished by using a thick wire bond pad. For this reason, and since the impedance of the strip lines on the package tend to be below 100 Ω, the spacing between the wires and the device substrate needs to be kept small. The modeling here extends that of [4] in focusing carefully on the problem of small wire height above substrate. A super-exponential behavior is shown for this regime, and excellent curve-fitted equations given to allow design.

We use the electrostatic (zero frequency) modeling package of Field Precision, Albuquerque, NM, which covers only TEM propagation and does not take into account dispersion due to quasi-TEM propagation. It should be noted that quasi-TEM propagation results in strip lines from a crowding of the field lines in the substrate at high frequencies ($\sim\ >50$ GHz). However, in a system such as here of conductors raised above the substrate, the dispersion may be raised to higher frequencies due to the air gap. This statement is based upon the fact that whereas in substrate-mounted conductors there are qualitatively two capacitances in parallel, the air and the substrate, for raised conductors the substrate capacitance also has air capacitances in series with it.

In Fig. 2, the equipotential lines of the transmission line cross section are shown for three cases, where $a = 0, d/2$, and d. Note the crowding of the lines between the substrate and the wires as they are raised very slightly above the substrate.

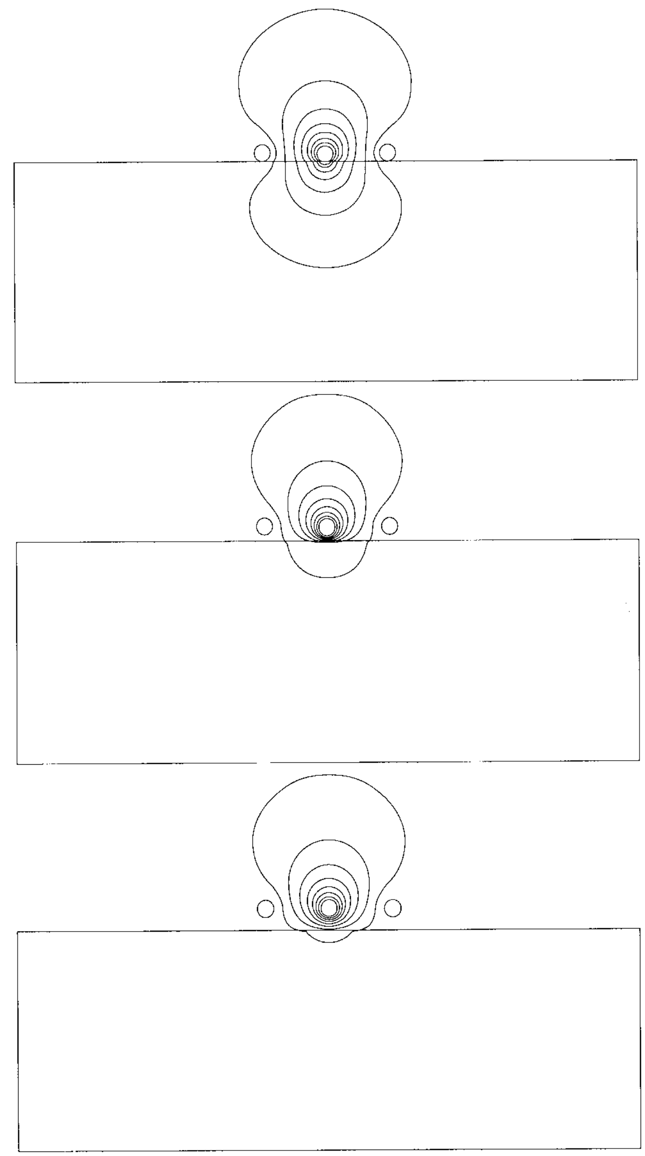

Fig. 2. Plot of equipotential lines of coplanar wire transmission line of Fig. 1, showing field crowding in the air gap as the wires are raised even slightly above the substrate.

Thus the effective dielectric constant rapidly goes from a value weighted between the substrate's and air to that of air as the wires are raised. The rapid decrease of the effective dielectric constant as the wires are raised is shown in Fig. 3. In Fig. 4, the natural logarithm of $(\varepsilon_{\text{eff}} - 1)$ is shown to illustrate that for $a/d > 0.3$, ε_{eff} follows an exponential decrease, while for $a/d < 0.3$ the decrease is super-exponential. For a device substrate dielectric constant of 13.1 (GaAs), a good overall fit is given by

$$\ln(\varepsilon_{\text{eff}} - 1) = c_0 - c_1(a/d) + c_2 \exp[-5(a/d)] \tag{5}$$

$$c_0 = 1.1 - 2.2/[(s/d) - 1]^{1/2} \tag{6}$$

$$c_1 = 0.3 + 0.7/[(s/d) - 1]^{1/3} \tag{7}$$

$$c_2 = 0.7 + 1.4/[(s/d) - 1]^{1/2} \tag{8}$$

and using $Z_0' = 1/(cC')$, where c is the speed of light in vacuum and C' is the capacitance per unit length, which is

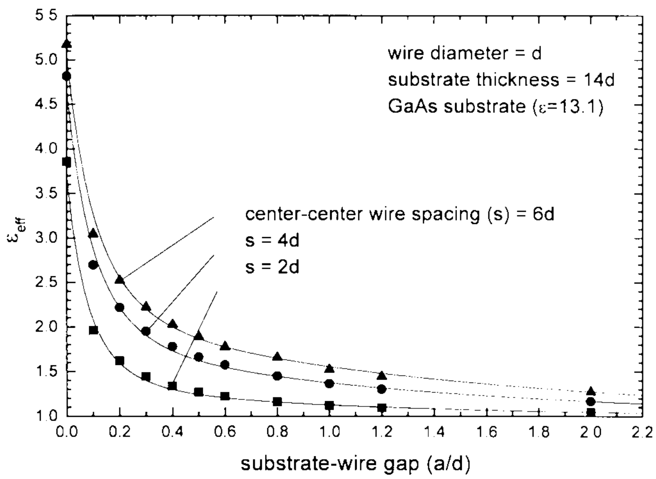

Fig. 3. Effective dielectric constant of coplanar waveguide wire transmission line of Fig. 1, showing enormous dependence on substrate-wire gap. The points are from the numerical modeling, while the curves are from (5)–(8).

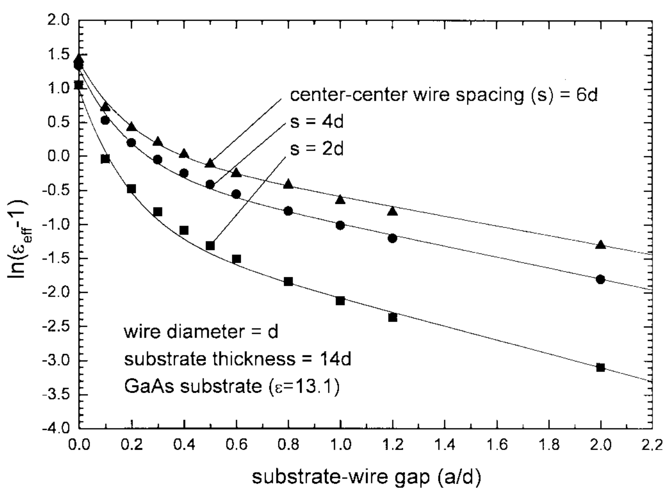

Fig. 4. Plot of natural logarithm of effective dielectric constant minus one. The points are from the numerical modeling, while the curves are from (5)–(8).

calculated using the program of Field Precision, Albuquerque, NM, a good fit for $2 < (s/d) < 10$ is given by

$$Z_0' = 140[(s/d) - 1]/\{1 + 0.6[(s/d) - 1]\}. \tag{9}$$

All these equations are for a substrate thickness of $14d$, and change little for different thicknesses.

Finally, Fig. 5 shows the characteristic impedance of the lines. To balance keeping the impedance as low as possible while not incurring great sensitivity to variations in gap, it is apparent that the substrate-wire gap should be where the behavior of ε_{eff} goes from exponential to super-exponential behavior, or $a/d = 0.3$. Even so, it will be difficult to keep the impedance below 100 Ω, and a matching network must be employed on the microstrip substrate.

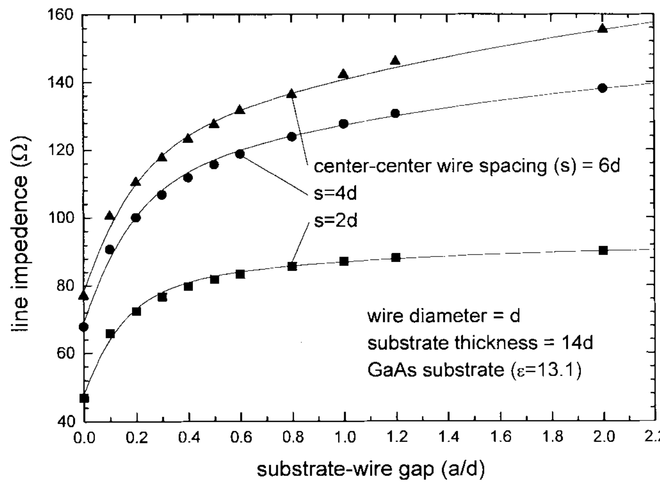

Fig. 5. Characteristic impedance of coplanar waveguide wire transmission lines of Fig. 1. The points are from the numerical modeling, while the curves are from (5)–(9), and $Z_0 = Z_0'/(\varepsilon_{\text{eff}})^{1/2}$.

The maintenance of constant wire-substrate gap depends of course of the maintenance of constant wire–wire spacing for impedance to remain constant along the length of the wires. Some package designs may require the wire–wire spacing to change along their length, for example, if the wire pitch is larger on the microstrip than at the device. In this case, the wires can still function as a transmission line if their gap also changes in such a way to maintain constant impedance according to (5)–(9).

In conclusion, a packaging structure has been proposed such that coplanar bond wires may be maintained at a constant height above the device substrate and so function as a transmission line. The characteristic impedance of such a "coplanar wire waveguide" transmission line has been determined as a function of its wire spacing and height above the substrate.

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