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PCB level Shielding for Portable Wireless Devices

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Abstract

As handheld wireless devices become lighter weight and more compact, the spacing between components on printed circuit boards (PCBs) has been greatly reduced. The high frequency nature of the signals in the components, the added functionality of the devices, and the desire to reduce PCB size are all driving the need for additional isolation and improved EMI (electromagnetic interference) shielding. New and creative shielding solutions are needed to address these challenging issues, while still meeting the low installed cost demanded by this high volume industry.

Perforated metal cans, both with and without removable lids primarily dominate current PCB-level shielding solutions. In this presentation, we will review the electrical issues dealing with EMI shielding at PCB-level, and highlight some of the problems with phenomena such as cavity resonance and aperture radiation. Test methods will be discussed that address the problem of testing the shielding effectiveness at PCB-level. Finally, a new PCB-level shielding technology will be introduced that solves many of the technical issues inherent to perforated metal cans.

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Purpose of PCB level shielding study:

- New shielding solutions are needed to address today's portable wireless devices:
  - Lower total height of PCB and components, with higher component densities
  - Contoured form factor and overall lighter weight
  - Higher frequencies
  - Low cost
- There is a need to study the effects of shielding enclosures as a part of the completed PCB assembly, in order to help develop new shielding solutions to solve these challenging issues

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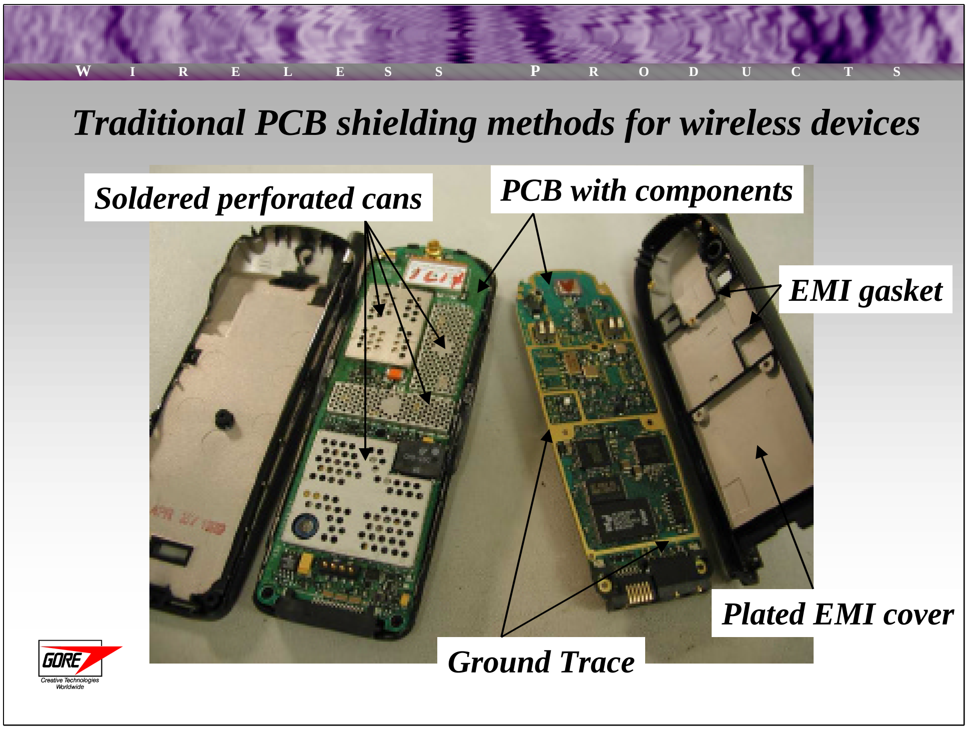
It is obvious that cell phones, wireless PDA's (Personal Digital Assistants), and wireless internet devices have been shrinking in size over the past few years. These smaller form factors make the mechanical packaging of these devices extremely difficult. This also drives the electronic circuitry to higher densities, not only because of physical size, but added functionality of the devices, such as multiple frequency bands, communication protocols, and added features such as GPS and digital photo capability.

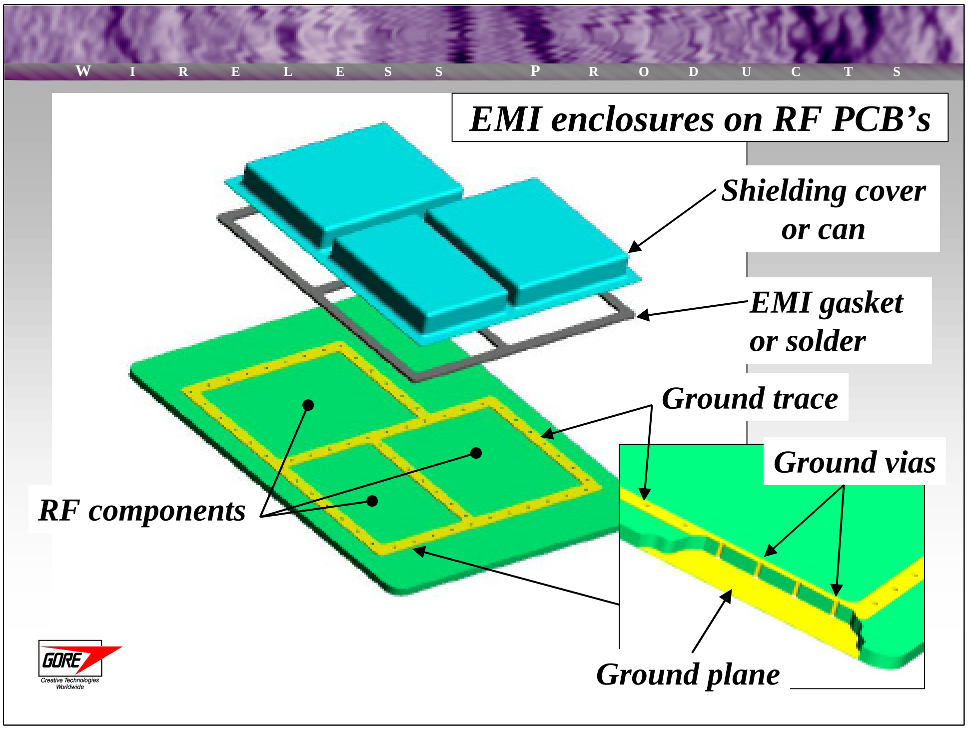
The traditional test methods, mostly coming out of military specifications for aircraft, etc. are not appropriate for such small, battery powered, portable wireless devices. There are some methods, such as ASTM D 4935 [1] for planar shielding and a coaxial cell [2] for EMI gaskets, that were developed to characterize the materials that would ultimately go into an EMI enclosure. To date, there has not been any formal methods published that would evaluate the effectiveness of a shield which is assembled to the completed PCB of a portable wireless device.

PCB level Shielding for Portable Wireless Devices

- **Background on shielding techniques**
  - **Two basic methods: Conductive gaskets and soldered cans**
- Design issues for shielding enclosures
  - Cavity resonance
  - Radiation from components on PCBs
  - PCB level shielding effectiveness measurements and test fixture development
  - Effects of apertures/gaps
- Using what was learned to aid in the development of a new PCB level shielding solution



Shielding technologies come in many forms, but two methods are primarily used in modern cell phone design: soldered perforated cans and plated covers with EMI gaskets. Each technology has its own set of advantages and disadvantages and are used for different reasons. In each case the goal is the same: to provide complete shields around the components on the PCB to achieve the electrical performance needed for the phone and compliance with regulatory requirements.



The goal of an EMI enclosure is to create a Faraday cage around the RF components by using the six sides of a metallic box. The top five sides are created using a shielding cover or metal can, while the bottom side is achieved by using the ground plane within the PCB. Ideally, if this were a perfectly solid metal box, there would be no leakage from within the box to the outside world, or visa-versa.

The reality is that there are several places EMI can leak from a shielding enclosure. Holes perforated into soldered cans, to allow thermal heat transfer during solder reflow, are typical. These holes can allow significant leakage through the shield, as will be seen later. Imperfection along the EMI gasket, or solder attachment can also provide areas of higher leakage. Another area that is sometimes overlooked are the spaces between the ground vias which electrically connect the shielding cover to the ground plane.

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PCB level Shielding for Portable Wireless Devices

- Background on shielding techniques
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- **Design issues for shielding enclosures**
  - **Cavity resonance**
  - **Radiation from components on PCBs**
  - **PCB level shielding effectiveness measurements and test fixture development**
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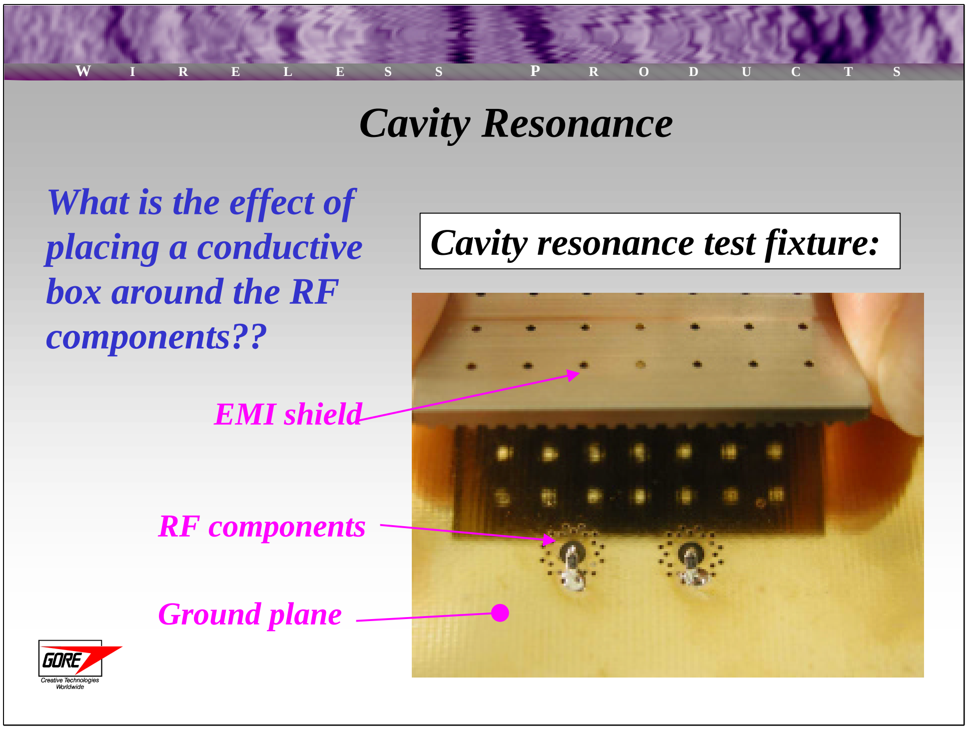
When designing shielding enclosures for portable wireless devices, several issues arise that needs to be considered. For modern cell phones that are lightweight and low profile, the mechanical constraints for the shield can be extremely challenging. Factors such as size, profile, weight, manufacturability, and total installed cost drive which shielding solutions are viable and which are not.

However, the electrical considerations can be equally as challenging. Phenomenon such as cavity resonance, aperture radiation, and planar shielding are factors RF engineers face when designing shielding enclosures. The problem is further complicated by the fact that accurate electromagnetic field prediction from complicated PCB assemblies, particularly in the near field, is virtually impossible. This forces engineers to build custom test fixtures to evaluate the performance of their shielding designs. Unfortuneatly, the industry has not adopted standard test methods or guidelines to evaluate different shielding solutions.



In order to create the Faraday cage required for proper shielding, a metallic enclosure must be placed around and in close proximity to the components on the circuit board. This may have adverse effects on the performance of the components and the functionality of the circuit. The largest concern would be if the metallic cavity resonated at any of the frequencies that the circuit operated within. To examine this point further, a simple test fixture was designed that would mimic the effect of placing a metallic enclosure over some RF components.

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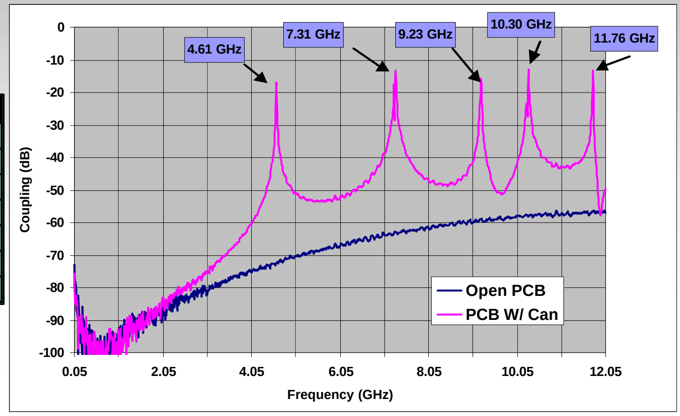
Cavity Resonance

$$f_c = \frac{c}{2p}\sqrt{\left(\frac{mp}{a}\right)^2 + \left(\frac{np}{b}\right)^2 + \left(\frac{lp}{d}\right)^2}$$

• For air filled cavities

Mode	m	n	l	fc (GHz)
TE	0	1	1	4.62
TE	0	1	2	7.31
TE	0	2	1	7.31
TE	0	2	2	9.25
TE	0	1	3	10.34
TE	0	3	1	10.34
TE	0	3	2	11.79



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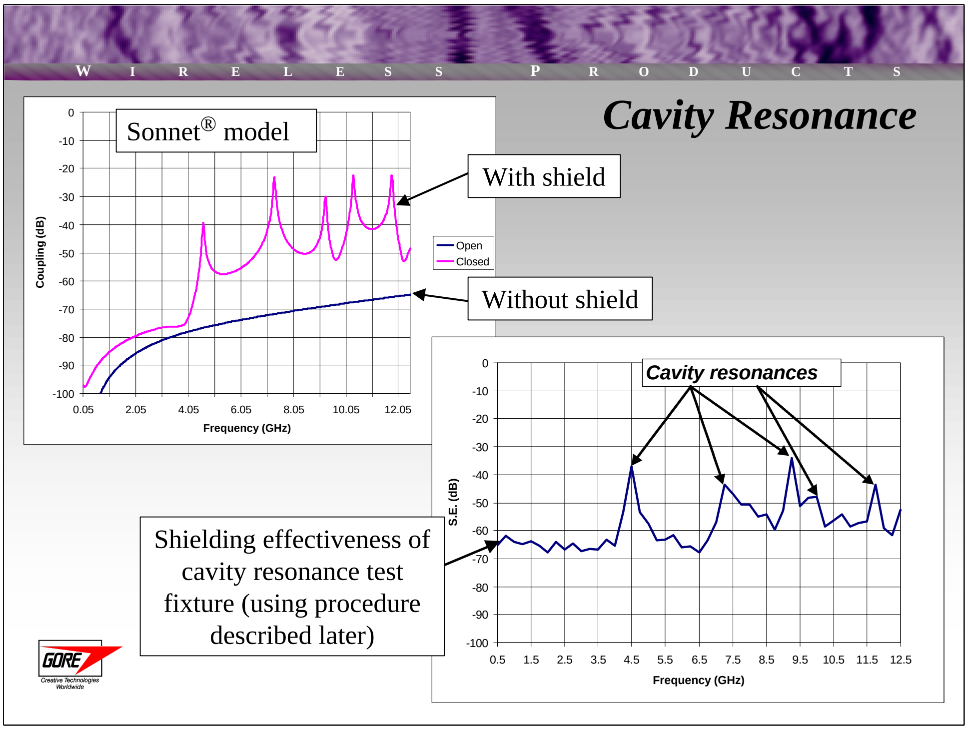
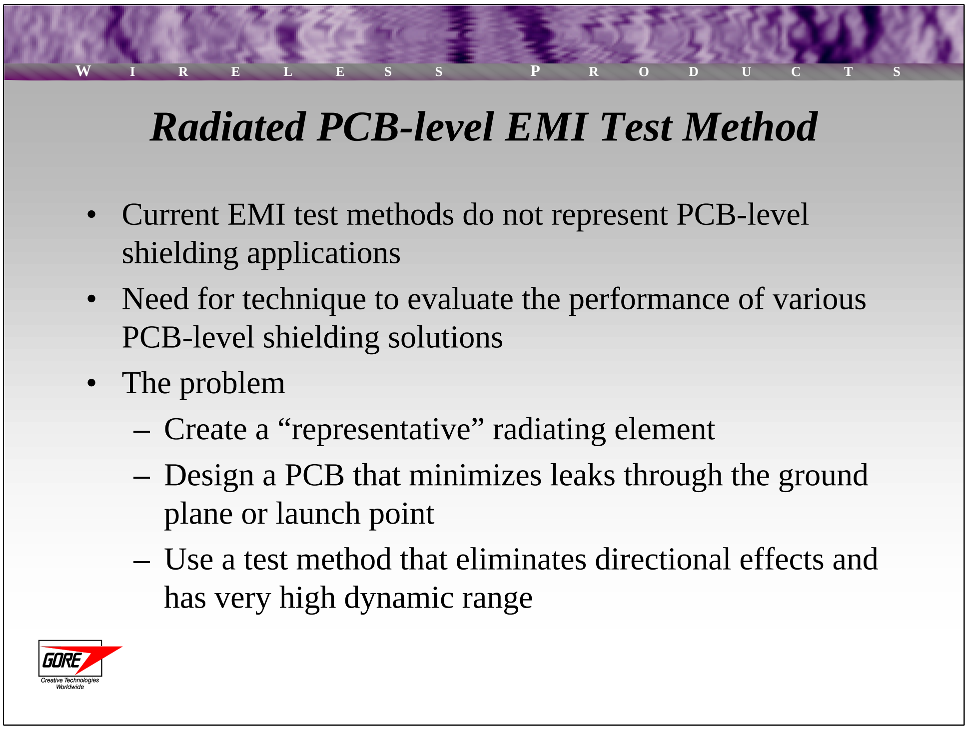
The test fixture shown is made up of two 50 ohm, 0805 resistors that are launched from SMA connectors from the opposite side of the ground plane. The spacing is arbitrarily set at 0.5 inches. This was done so that very little coupling would occur between the two components when the shield is not in place (as shown in the above graph). The coupling was obtained using a measurement of 20 log(S_{21}) from a vector network analyzer. A perforated metal square can, with inside dimensions of 1.805 inches square by .114 inches high was soldered over the components. This was done to illustrate the effects of placing a metal cavity over components. The simple formula shown is used to roughly calculate the resonant modes of the EMI enclosure. This formula is only used for rectangular shaped cavities and is fairly accurate if the cavity is filled with air. However, most enclosures on PCBs will include the circuit board material and components within them, which will raise the effective dielectric constant within the cavity, thus lowering the resonant frequencies of the cavity.

With the shield in place, the coupling between the two components is severely increased at and around the resonant frequencies, as much as 50 dB for this test fixture. The peaks occur at the calculated resonant frequencies provided by the formula. It is also important to note, that below the first resonant frequency, the coupling between the two components is virtually unchanged. This example shows why it is critical to consider these resonant conditions when designing EMI enclosures.



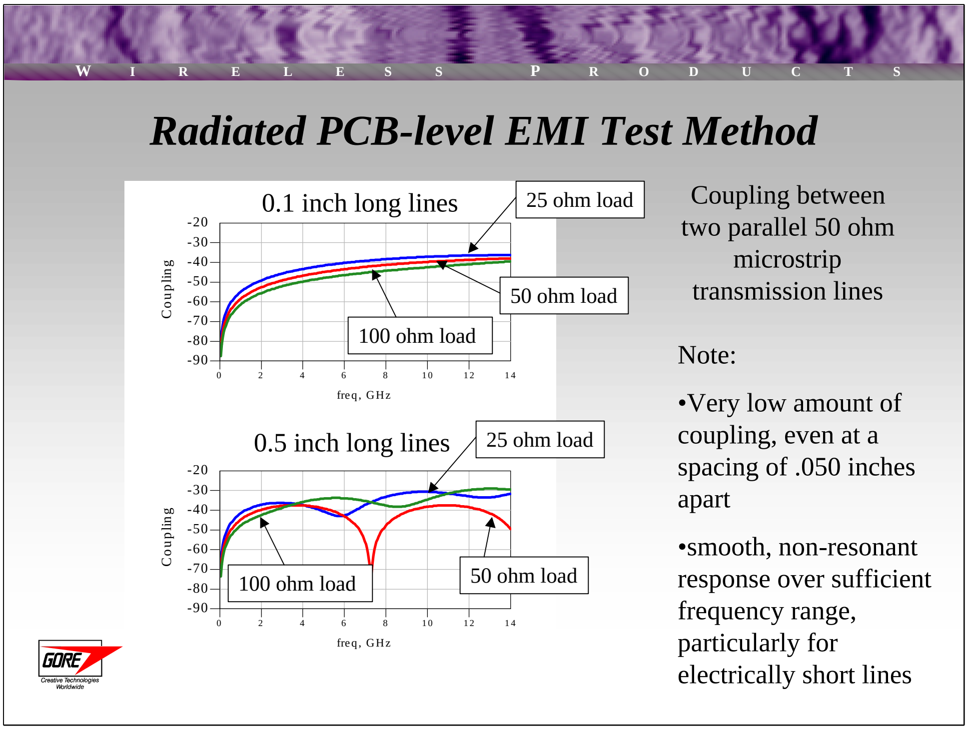
A more accurate way of predicting the effects of a rectangular cavity would be to use an electromagnetic field simulator, such as the Sonnet® Professional Planar Software Suite. This software models planar circuits within a metallic box, and can easily be used to examine the effects of cavity dimensions, substrate material, and metal wall conductivity. A free "Lite" version is available on their web site at (http://www.sonnetusa.com). The graph above shows a model produced by the software, with and without the metal lid attached to the cavity. There is excellent agreement between the model and the actual measured data.

Another important consideration concerning cavity resonance is the effect on the shielding performance of the enclosure. Since the energy inside the cavity is amplified at the resonant modes, it stands to reason that the shielding effectiveness would also be worse at these frequencies. The plot above shows the shielding effectiveness of the same resonant cavity test fixture (using the method described later). The shielding effectiveness is significantly worse at and around each of the resonant frequencies of the cavity. This is an unavoidable problem, since it is due to the dimensions of the cavity. This will be an important point later on when PCB level shielding effectiveness testing is discussed.



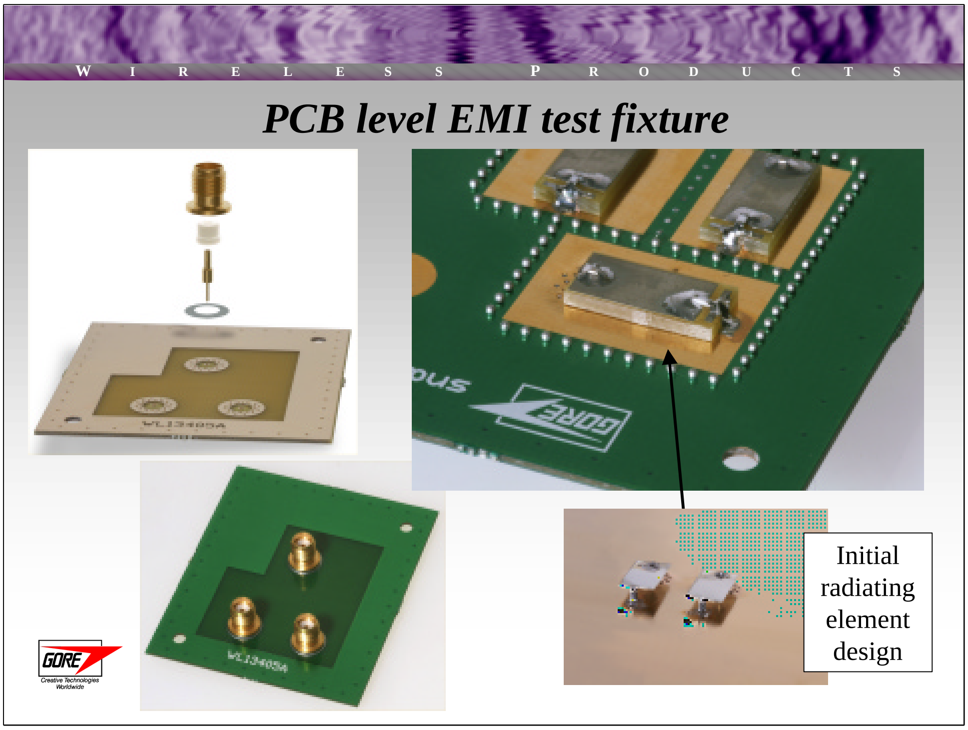
If the methods for testing the effectiveness of PCB level shields were to be broken into three categories, they would be: Compliance testing, functional testing, and indirect testing. Compliance testing involves evaluation of the final product given industry standard test methods and acceptance levels, such as spurious emissions, susceptibility, or ESD (electrostatic discharge). Functional testing would be described as a “self-compliance” testing criteria. In this manner the device is tested for performance requirements usually described by the manufacturer. Intercavity shielding, radiation from antenna back into receiver, and phase noise are examples of parameters that would be considered.

Even though the industry ultimately relies on the first two methods for the final determination of shielding effectiveness, the last category, indirect testing, is the one that is used when describing shielding products. Methods such MIL G 83528B, ASTM D 4935, ASTM D 991 are methods that suppliers use to evaluate their shielding products. These methods attempt to characterize the constituent properties of a shield, but lack the ability to predict the performance in a specific application. Creating a test vehicle that will ultimately predict the shielding performance in a particular application is virtually impossible to do. However, there is a lot of interest in having test methods for shielding products that more closely mimics the end user’s device.



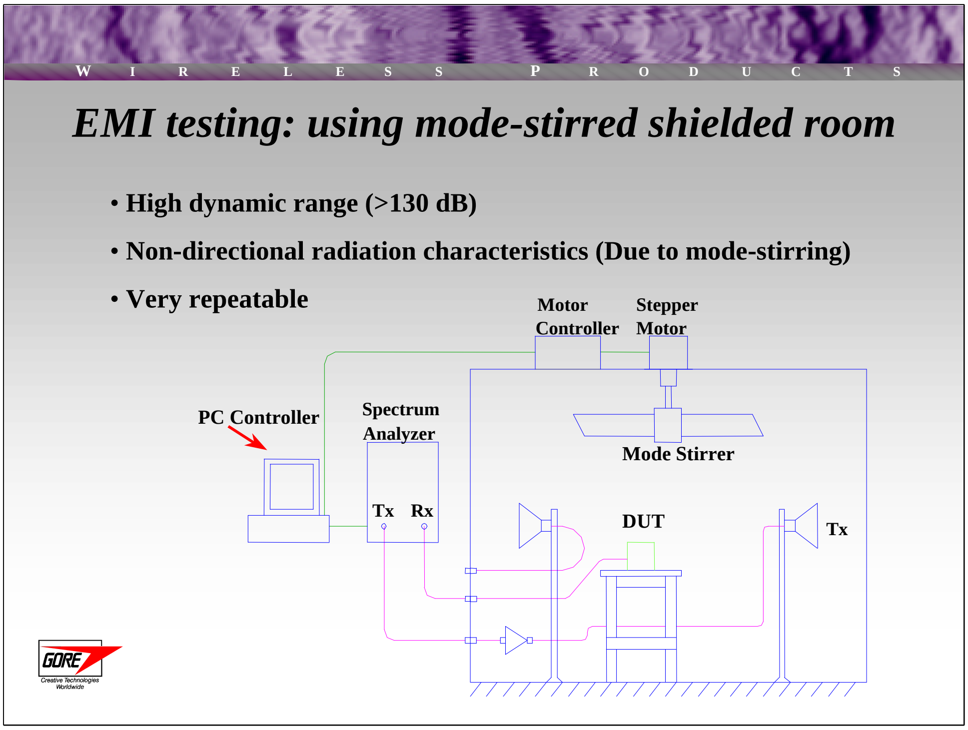
Typical SMT components are not designed to radiate, otherwise the circuits would not work. Based on their small size, the radiation characteristics are going to be small, but not necessarily negligible. Predicting the radiation response, particularly in the near field, of typical SMT devices is a formidable task.

A good place to start in understanding the problem is to first consider the coupling between two microstrip lines that would be used to connect components on the PCB. From the graphs above, it is apparent that, for short transmission lines, the coupling between two parallel lines is very low, even if they are close together. We can use this as a starting point in developing an inefficient radiator that can be used in a test vehicle. First, since the dielectric substrate thickness on the outer layers of the PCB is usually very thin, it is desirable to have the radiating element be a separate component, instead of integrating it onto the PCB itself. This gives you the freedom to vary the height of the radiator, and yet keep it sufficiently lower than the inside height of the shield. Next, if you take the remaining dimensions of this transmission line-like element (the height, length, width, and termination impedance) you can optimize the response of the radiator that would give favorable characteristics for testing the shields on wireless PCBs. The results of this work are shown on the next slide.



A special test fixture was designed to closely mimic the radiation from typical surface mount components. The goal is to create a simple test component that has “inefficient” radiation characteristics, and has a fairly smooth, non-resonant frequency response over a sufficient frequency range. The height, length, width, termination impedance, and substrate material were optimized to achieve these characteristics.

At the bottom of the PCB is a custom designed SMA connector that, using a solder pre-form, completely seals the launch point to the ground plane of the PCB. The connectors then feed the radiating elements that are attached to the opposite side of the PCB. The shields would then be centered and attached over each of the elements.



The mode stirred reverberation chamber technique, described in Ref [4] and [5], is an excellent EMI test method because of its high dynamic range and repeatability. In this technique, the radiation characteristic from the device under test, is compared to that of a reference horn antenna. The procedure would be to first measure the reference horn as the device under test (DUT). Then the horn is swapped out for the real DUT, which in this case is the PCB level shielding test fixture. Of course, only one radiator/cavity can be tested at a time. The radiator is first measured without a shield over it, then the shield is attached and the device re-measured. The shielding effectiveness would be calculated as the difference between the received power levels (in dB) before and after the shield is applied .

The frequency range of the test is determined by the room dimensions, the test equipment used, and the antenna bandwidth. The main limitation with this test method is usually the lower frequency boundary, which is determined by the size of the room and antenna used. For the tests in this report this frequency range spans from about 1 GHz to 13 GHz.

EMI testing: using mode-stirred shielded room

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Where do slots, or apertures occur within the shielding enclosure?

- Perforations in the shield, as found in stamped metal cans
- Discontinuous shields caused by removable lid cans
- Breaks along the shielding gasket
- Spaces between the grounding vias
- Relief areas in the ground plane layer of the printed circuit board (PCB)

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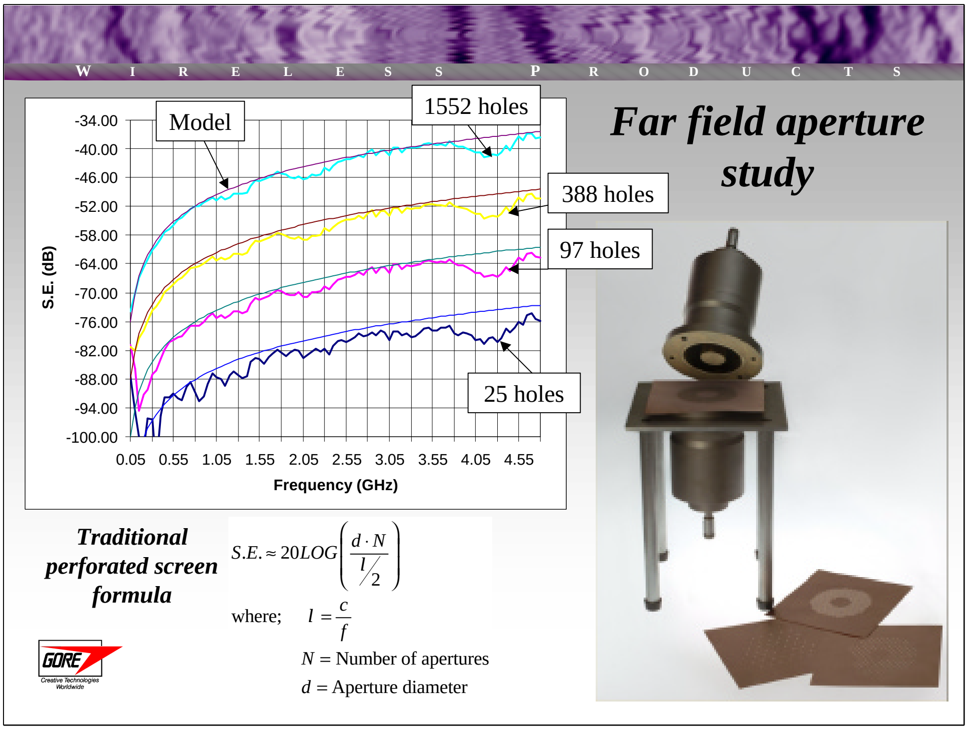
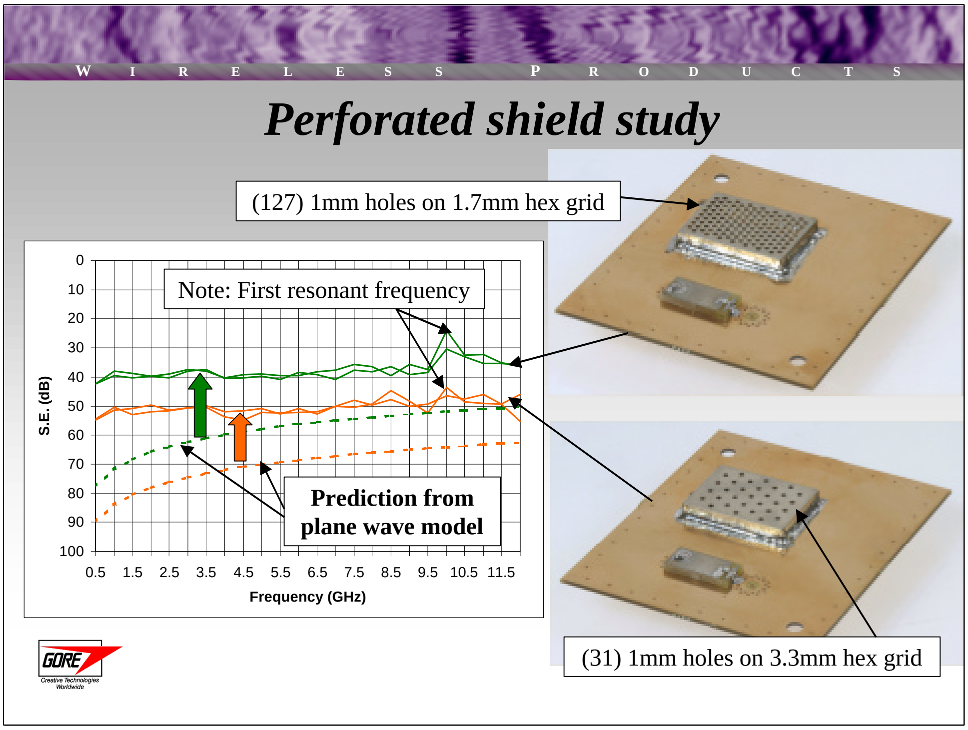
Practically, EMI enclosure cannot be made to be a complete Faraday shield. Gaps due to perforations in the shields, or incomplete shields, breaks in the shielding gasket, spaces between grounding vias, and relief areas in the ground plane are necessary to manufacture the complete circuit board. There are rules-of-thumb that say that as long as the size of the aperture is much smaller than the wavelength of the highest frequency of interest, it should not cause an appreciable amount of leakage.



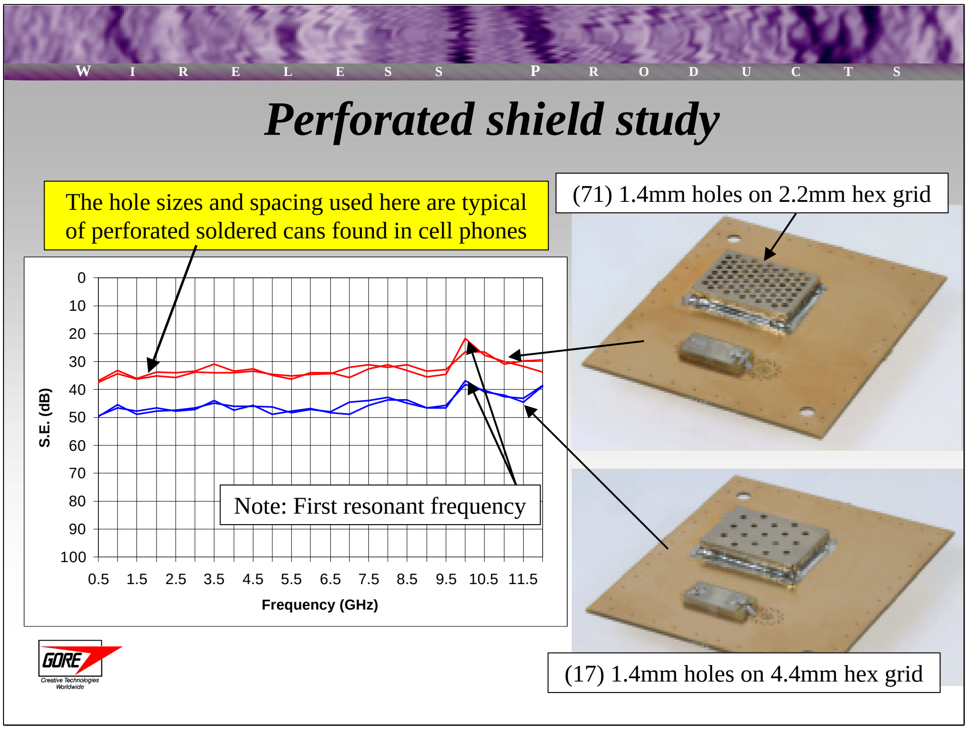
The effects of apertures that are much smaller than a wavelength at the highest operating frequency of interest has been studied to great lengths [9]. For perforated screens, the above formula has been used to show the frequency relationship between the size of the aperture and the shielding effectiveness. Although this frequency dependence represents an accurate relationship for a far field responses, an offset factor in S.E. can deviate quite a bit from real life applications. To get around this, a relationship for the far-field (plane wave) response was derived using empirical data taken from thin copper sheets perforated using the traditional hexagonal pattern. Initially, 1mm diameter holes were placed on a 1.7mm hexagonal grid, such that about 1552 holes fell within the annulus of a typical ASTM D 4935 test cell. The shielding effectiveness was obtained using measurements from a vector network analyzer, 20 log(S_{21}), with and without the sheets in place (shown in the above graph).

Using the above formula, and a correction offset factor, a simple model was generated to represent this test pattern (also shown above). The next three test patterns were generated by doubling the spacing between the holes each time. This way, about 4 times less number of holes fell within the annulus of the coaxial cell for each pattern. The data is shown above with the corresponding model overlaid. To generate the modeled data, the original model was changed by a factor of 4 each time, which yielded 12 dB offsets. As can be seen, the frequency relationship follows what would be expected for plane wave excitation of perforated thin sheets.



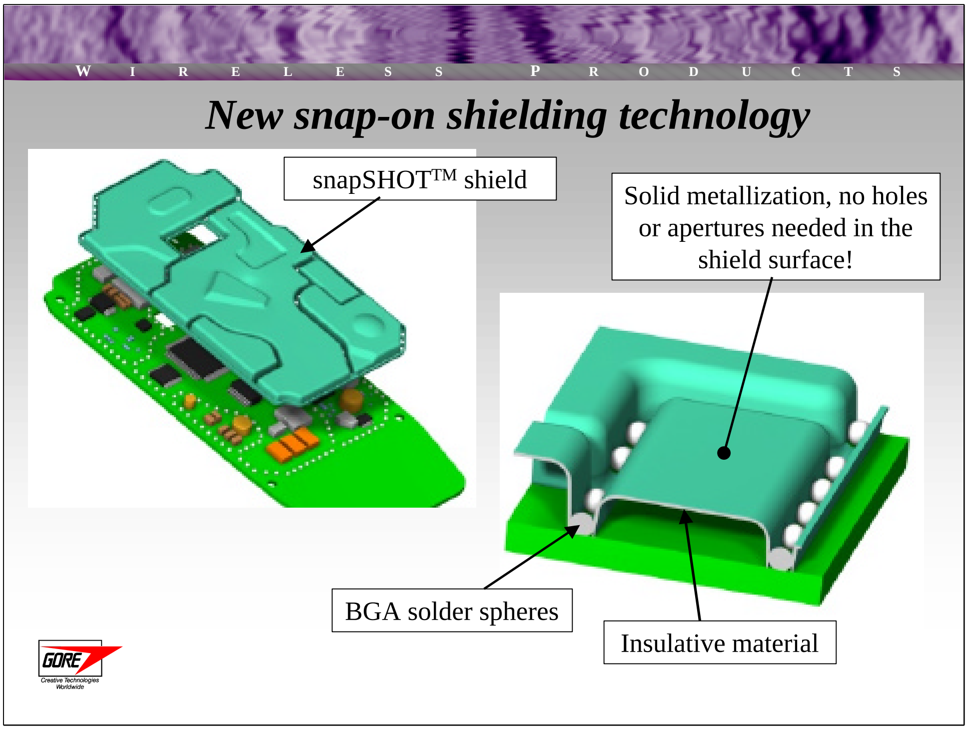
The next logical step is to see how a perforated soldered can would perform using the same 1mm hole size on a 1.7mm grid. Using the test method described earlier, a 16.3mm wide by 22.5 long by 3.1mm high can, completely soldered around its perimeter , was used as the shield. Using the model generated from the plane wave experiment, a prediction was made for (127) 1mm holes. The actual shielding effectiveness data is shown above along with the model (in green). The surprising result of an overall lower shielding effectiveness is added to the fact that the response is flat with frequency, even at low frequencies. This shows that even at low frequencies, where the size of the apertures are extremely small compared to the wavelength, the S.E. remains unchanged. These results are eluded to in the literature [9] and [11], but have not been generally well understood. Cooperative research with the University of Delaware, using custom method of moment software, has confirmed these results and will be published formally at the 2003 IEEE EMC symposium in Boston, MA.

If the spacing of the apertures is increased by a factor of 2, thus reducing the total number of holes by a factor of 4, the S.E. is increased, or shifted by about 12 dB, the same as the plane wave case.



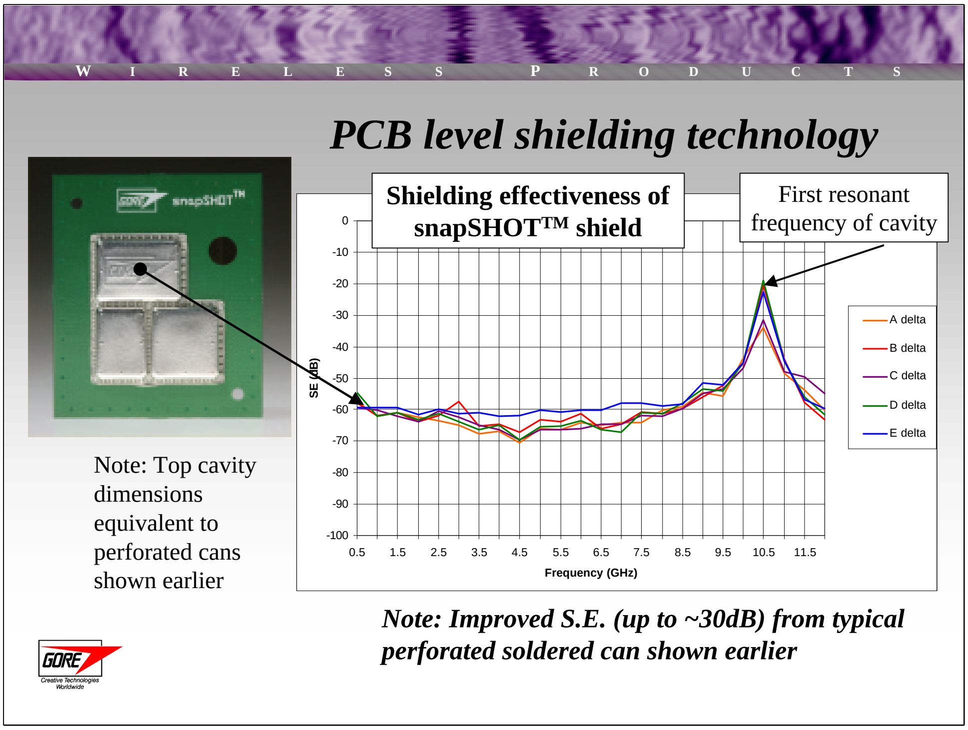
The reason manufactures put perforations into the can in the first place is to allow for heat transfer during the solder reflow process. Since these cans are attached to the PCB using the same SMT process as the components, they must not affect the reflow of the components under and around the shields. In typical applications, hexagonal arrays of sufficiently sized holes are placed over the entire top surface of the can. A hole size is 1.4mm and larger is typical with the hexagonal grid yielding a hole spacing of 4.4mm and smaller.

- ***How can we use what was learned to aid in the development of new PCB level shielding solutions?***
  - A test method was developed to provide a measurement of S.E. for PCB level shields
  - Cavity resonance can impact coupling within the shield and the S.E. provided by the shield
  - The S.E. for perforated soldered cans is significantly worse than traditional plane wave theory would predict. This result is due to coupling between the apertures and the radiating element, and is supported by measured data and theoretical development by the University of Delaware
  - Since apertures in soldered cans are necessary for the SMT solder reflow process, removing them is not a desirable option
  - ***An improved PCB level shielding solution would remove all possible apertures, yet maintain high volume manufacturability and ease of rework***

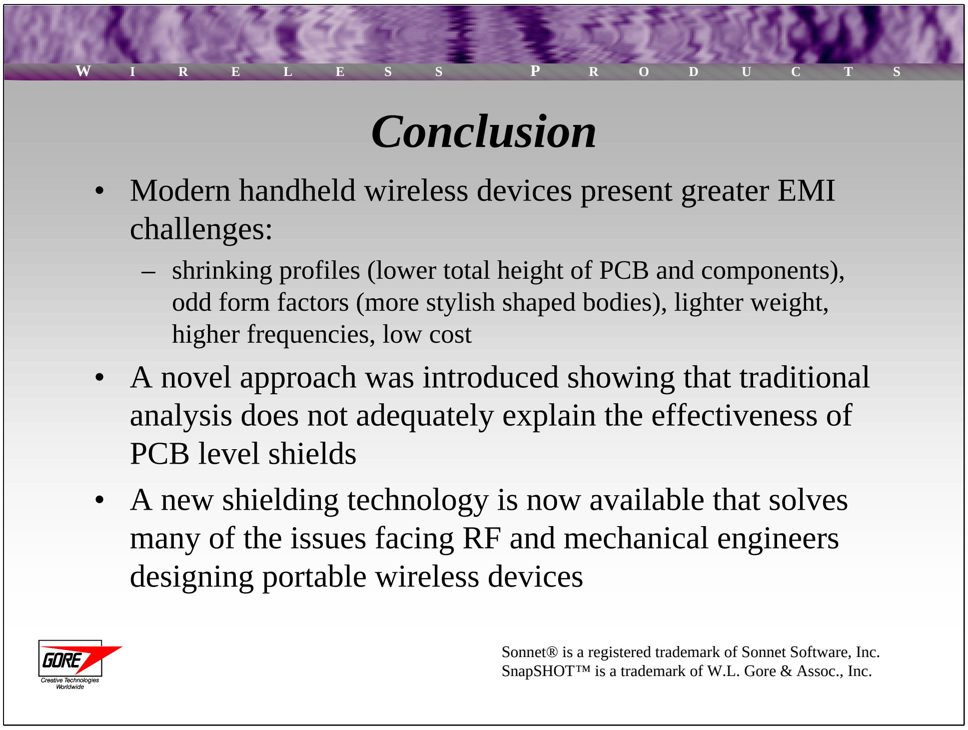


Gore has developed a new shielding technology called snapSHOTTM shield. This new “snap-on” shield solves many of the problems with the current soldered cans. It is a fully integrated shielding solution that consists of of a metallized thermoformed shell, which is attached to the PCB using standard ball grid array (BGA) solder spheres. These snap-attachment features provide an excellent mechanical and electrical connection and yet allow the user to easily remove the can to get access to the components within the shield. This patented technology (US patent #6,377,475; other US and foreign patents pending) offers a PCB level shield that can be easily attached to a populated board after it has gone through the solder reflow process. This allows manufacturers to test, inspect, and rework a completed PCB before they attach the shield to the board.

The shield is made from a high performance material that is metallized on the outside surface and insulative on the inside. The BGA spheres make contact with the outside surface by snapping through holes in the shield, thereby creating a robust electrical and mechanical connection to the PCB. The periodicity of the sphere placement is determined by the shielding performance required. Since the inside surface of the enclosure is non-conductive, any components that may come in contact with this surface will not be electrically shorted.



As can be seen by the above data, snapSHOT™ shield provides significantly improves shielding over similar perforated solder cans (as shown in the previous slides). Besides the excellent shielding performance that snapSHOT™ shield provides, it also gives designers unprecedented flexibility in laying out and designing shielded enclosures. Due to the thermo-forming process, designers can create very complicated shapes and profiles with multiple cavities of different heights, rounded edges, and still maintain the narrower ground trace widths needed between the cavities. The finished product is an extremely lightweight and cost effective shield for modern portable wireless devices.



Author Bios:

Tom Clupper is an RF Engineer with W.L. Gore & Assoc., Inc. Spent 17 years with the RF and Microwave products developing numerous products in the areas of cable and interconnects through 65 GHz. He has performed materials research and product development in the areas of dielectric substrates and EMI shielding materials. BSEE from Penn State and an MSEE from the University of Delaware.

Joe Rowan: Global Business Leader for Gore's Wireless Interface Products Group, including GORE-SHIELD® EMI shielding solutions. Spent most of his 18 year Gore career working with RF and Microwave products, and owns several patents in this area. Member of IEEE and IEE, co-chaired P1302 working group on EMI gasket testing. BSEE from Napier University in Edinburgh.

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