Product Application Note **March 29, 2002**

Design Guidelines for Microwave Cavities

Background: Placing a microwave circuit, active or passive, in a cavity below its waveguide cut-off frequency will decrease the effects of radiating signals (such as feedback, gain ripple or decreased isolation) from the microwave elements.

Method: The theoretical equation for the lowest waveguide cutoff frequency (mode TE01) for a rectangular waveguide is

$$Fc = c / 2b$$

where Fc = cutoff frequency (Hz)
c = speed of light (3x10^8 m/sec)
b = longest dimension of the rectangular waveguide cavity (meters)

This equation assumes a dielectric constant of 1 (air). In reality, the waveguide cavities with microwave circuits contained therein are partially filled (usually <10%) with a substrate that has a dielectric constant greater than 1. There exist more complicated design equations that can calculate the cutoff frequency for a partially filled cavity, but this extra complexity is usually not worth the effort. The many other factors that influence the characteristics of radiating signals, such as bondwires, circuit patterns, or passive components, typically have a larger effect on the final result.

A second equation is used to calculate the attenuation of the microwave signal as it travels down the waveguide channel even though it is below the cutoff frequency. This is called the evanescent mode; the signal strength decays rapidly with distance and is proportional to the ratio of the cutoff frequency to the signal frequency

$$\text{Alpha} = \text{sqrt}\left((pi/b)^2 - (2*pi*f/c)^2\right)$$

where Alpha = attenuation constant (Nepers/m)
pi = 3.14159
b = dimension of waveguide (meters)
f = signal frequency (Hz)
c = speed of light

Then the attenuation in dB is,

$$\text{Attenuation} = 20*\log(\exp(\text{Alpha}*z)) \text{ dB}$$

where z = length of waveguide channel (meters)

For microwave circuits with a lot of gain (30+ dB) or with a high isolation requirement (such as the stopband of a filter) a good rule of thumb is to make the cutoff frequency 3x to 4x the highest signal frequency of interest. As the gain or isolation requirements moderate the cutoff frequency can be moved closer to the signal frequency (the microwave channel can get wider).

Examples:

Design #1:

Design a stable amplifier chain consisting of four 20 dB amplifiers and 10 dB of losses (attenuators and filters) at 7 GHz.

Objective: Reduce the non-propagating signal in the channel from output back to the input by 40 dB greater than the forward gain (70 + 40 = 110 dB loss). With the feedback signal 40dB lower than the input signal a gain ripple (or error) of less than 0.1 dB is expected due to the worst case vectoral addition of these two signals. The equations for this calculation are

Amplitude error (worst case, additive) = 20 * log(1 + 10^(fb/20))
Amplitude error (worst case, subtractive) = 20 * log(1 - 10^(fb/20))

Phase error (worst case) = arctan(10^(fb/20))

Where fb = level of feedback signal relative to the level of the main signal in dB.
This value will be negative if the feedback signal is smaller than the main signal at the input (as it needs to be).

The waveguide channel dimension was limited by the size of the filters to 0.25 inches (b dimension). The length (z dimension) of the channel was approximately 0.90 inches. So the cutoff frequency is

Fc = c / 2b = 3e8 / (2*0.25 / 39.3701) = 2.36e10 or 23.6 GHz

The calculated attenuation of the evanescent wave at 7GHz is

Alpha = sqrt((3.14159/(0.25/39.3701))^2 – (2*3.14159*7e9/3e8)^2)
= sqrt(2.45e5 - 2.15e4)
= 473 Np/m

Attenuation = 20*log(exp(473*0.9/39.3701)
= 93.9 dB

This value is less than the desired 110 dB of loss required for this design, but it doesn't take into account the probe losses – the gain of the "antenna" that launches the signal from the microstrip environment to the waveguide mode. In this design the most effective radiating element was the 5-pole bandpass filter that was at the output of the amplifier chain. It is very difficult to calculate the loss from imperfect antennas such as filters or bondwires. However, it was estimated that this filter had an "antenna gain" of no more than –10dB. At the input to this amplifier chain, the "receiving antenna" was considered to be the bondwires attaching to the input of the first MMIC. Their gain had to be less than –10dB (since they are so much smaller than the filter elements) so it was considered that this design met its goal (93.9 + 10 + 10 > 110dB). The empty waveguide cavity was measured with simple 50 ohm lines placed into each end and two bondwires attached to their ends. The measured isolation was greater than 110 dB (the value exceeded the dynamic range on the instrument). The completed design, with all amplifiers and filters in place in the narrow channel, exhibited a feedback signal more than 110 dB below the output signal.

Design #2:

Microstrip edge-coupled bandpass filters are often used at millimeterwave frequencies because of their compact size, lack of vias, reasonable line width/spacings, and good performance (insertion loss, bandwidth, filter selectivity).

Objective: Design a bandpass filter at 25 GHz with a 5% passband and 40dB rejection at 0.95*center frequency. Achieve flat passband response and a 40dB loss in the stopband while taking into consideration the variables affecting the filter performance such as substrate dielectric constant, substrate height, line width/spacing dimensional tolerances and temperature.

After estimating the influence of all of the variables a filter can be designed with sufficient margin to meet the specifications. It is typically a 5 to 7 section design. When tested on an open carrier plate however, the lower frequency skirt of the filter misses the 40 dB rejection level at the specified frequency by 15 to 20 dB. This is due to the resonators of the filter radiating a portion of the signal which is "received" by the next resonator. A linear circuit simulator cannot predict this response because it doesn't include radiative coupling between the open ends of the resonators.

The solution is to place the filter in a waveguide cavity. The chosen width of this cavity was 0.12 inches and the filter length was approximately 0.3 inches. The design values are

$$F_c = 3e8 / (2*0.12/39.3701) = 49.2 \text{ GHz}$$

Alpha = sqrt((3.14159/(0.12/39.3701))^2 – (2*3.14159*25e9/3e8)^2)
= 886 Np/m

Attenuation = 20*log(exp(886*0.3/39.3701) = 58.6 dB

Even though this cavity produced a cutoff frequency-to-signal frequency ratio of only 2x, it was sufficient to bring the response back to the predicted values. In the absence of radiated energy the shape of the filter matched the simple linear model. Also, the interaction with the lid (reflections) was low enough to avoid the use of absorber.

These equations provide a good first order approximation to the problem and can sometimes highlight serious radiation issues before the design is frozen. Due to the many other variables which can add to, or subtract from, the radiating or propagating signal (bondwires, substrates, microwave structures, filters, passive components, etc), it is best to stay as conservative as the design will allow. At higher frequencies such as 40 GHz it becomes difficult to build a channel below the waveguide cutoff frequency (b=0.147 inches at 40 GHz) and still support the circuit element sizes. To achieve a 3x ratio at 40 GHz would require a channel width of 0.049 inches and a height from module floor to lid less than this value.

If the design dictates that active components, such as MMIC amplifiers, be placed in a **propagating** waveguide channel, it is prudent to limit their gain to 20 or 30 dB maximum. The use of absorber on the lid in this case will almost always be required and some gain ripple due to radiative feedback of the output signal can be expected. The best course of action is to keep everything very close to the ground plane. This reduces to a minimum the radiation of components such as bondwires and other transitions. It is not uncommon for a MMIC amplifier with 15 or 20 dB of gain to lose about 1 dB when a lid with absorber is placed above the MMIC. This is an indication that the radiative signal level is not negligible.

Recommended Approach:

1. Use cavities below waveguide cutoff as needed to eliminate radiative signals. A ratio of 3x to 4x (cutoff frequency to signal frequency) is advisable.
2. Minimize gain at high frequencies whenever possible.
3. Break up gain into smaller blocks (place filters between gain stages) especially if the amplifiers are in a propagating cavity or near the cutoff frequency.
4. Use absorber to reduce reflections from the lid. This is often necessary even in small channels well below the cutoff frequency.

For additional information, please contact TriQuint Texas Applications Engineering Department at 972-994-3647.