The Impact Of Crossing A Reference Plane Cutout On The Signal Integrity Of High Speed Signals When A Stitching Capacitor Is Available To Support The Return Current

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***Abstract*—A good engineering practice for alleviating the signal integrity degradations due to high-speed signals jumping across a reference plane cutout is to use a capacitor that bridges the cutout, so that the signal's return current can mostly follow alongside the source current. This approach is well known for mitigating the radiated emissions from the propagating signal. However, little is known about the capacitor values that are needed to support this application from a signal integrity perspective. Moreover, the physical size of these "stitching" capacitors needs to be very small in order to minimize the needed printed circuit board real estate for this application. Conventional 0603 capacitors are too large for this application when the cutout is small in its size. In this case, 0402 or 0201 capacitors are needed for this application. By doing so, the available values for these smaller capacitors are limited from 0.5pF to 100pF for the 0201 capacitors, and from 0.5pF to 470pF for the 0402 capacitors. Therefore, it is of interest to understand the minimum needed capacitance for providing good signal integrity performances for high-speed signals. This paper attempts to extract this understanding by providing simulated output eye patterns for a 10Gbs propagating signal with a 40ps risetime. In addition, this paper extends this study by determining the impact of jumping across several small reference plane cutouts on the signal integrity of the 10Gbs signal.**

I. INTRODUCTION

In a previous paper, it was disclosed that a reference plane cutout induces an inductive discontinuity along the path of the propagating signal. In addition, it was shown that the cutout induces a low-pass frequency response, as was shown in the S_{21}(f) forward transfer function. The geometrical attributes of the cutout are given by the width of the cutout, *X*, and the height of the cutout, *Y*. Finally, it was shown that the level of signal degradations to the propagating signal depended directly upon the relationship between the risetime frequency, $1/(2t_r)$ Hz, and the 3dB bandwidth imposed by the cutout. The ristime frequency, denoted by f_{max}, is equal to $1/(2t_r)$ Hz, and is the frequency associated with the risetime of the propagating signal. Very little signal degradations occur whenever $f_{max} << f_{3dB}$. As f_{max} approaches f_{3dB}, the signal degradations become more significant. The level of the signal degradations were maximized whenever $f_{max} > f_{3dB}$. It was also noted that the cutout did not need to be large to inflict significant signal integrity degradations on the propagating signal. Significant signal integrity degradations occurred with *X=40mils* and *Y=100mils*, for example.

In this paper, a stitching capacitor is used to help guide the return current directly alongside the source current. Figure 1 highlights this kind of situation.

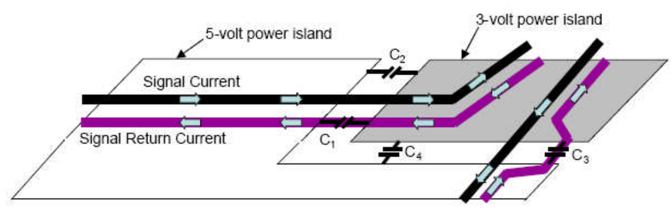

Fig. 1. Capacitors C_1 through C_4 are used to help guide the return currents alongside the source currents.

From Fig. 1, a 5-volt power plane is AC coupled to a 3-volt power plane through the use of four capacitors. By doing so, the return currents mostly propagate alongside their source currents. This result tends to minimize the loop areas associated with those parts of the signal paths that cross the gap, or cutout, between the two power planes. Some gap areas can be rather small, on the order of about 40mils X 50mils, for example. In these cases, conventional 0603 capacitors may be too large for this application. Instead, 0402 or 0201 capacitors might be used for guiding the return currents back to their sources.

By doing so, the available values for these smaller capacitors are limited from 0.5pF to 100pF for the 0201 capacitors, and from 0.5pF to 470pF for the 0402 capacitors. The placement of the capacitors across the cutout then adds a third return path for the currents. The first and second return paths include the upper and lower halves of the cutout, as described in a previous paper. Therefore, the return current will traverse these three separate paths back to its source.

The net effect of the reference plane cutout is to induce an inductive discontinuity along the propagation path. Based upon the two contours that are traversed by a portion of the return current along the upper and lower halves of each cutout, the value of this inductance can be estimated. For example, this inductance can be estimated by using the following closed form formula that was derived by the author:

$$L(X,Y,d) := 5.08\cdot\left(X\cdot\ln\left(\frac{Y}{d}\right)+\frac{Y}{2}\cdot\ln\left(\frac{X}{d}\cdot 2\right)\right)$$

The units of L(*X,Y,d*) are nano-henries. The variable *d* represents the width of the contours taken by the return current around the upper and lower halves of each cutout. For example, the value of *d* is typically 1-2mils. It is important to note that *X*, *Y*, and *d* must be in units of inches when using this formula. It should be intuitive that smaller values of *X* and *Y* yield smaller inductive discontinuities. For example, when *X=20mils* and *Y=20mils*, the inductive discontinuity is equal to 0.39nH. On the other hand, when *X=40mils* and *Y=40mils*, the inductive discontinuity is equal to 0.98nH. A current divider is then formed between the two halves of the cutout, as well as the capacitor.

II. SIMULATION RESULTS

When the propagating signal encounters a reference plane cutout, the inductive discontinuity, as well as the stitching capacitor, causes reflections to occur at this boundary. Figure 2 shows the $S_{21}(f)$ forward transfer function, between 0Hz and 20GHz, when the propagating signal encounters a cutout with *X=40mils* and *Y=100mils*. In this case, the stitching capacitor has a value of 20pF.

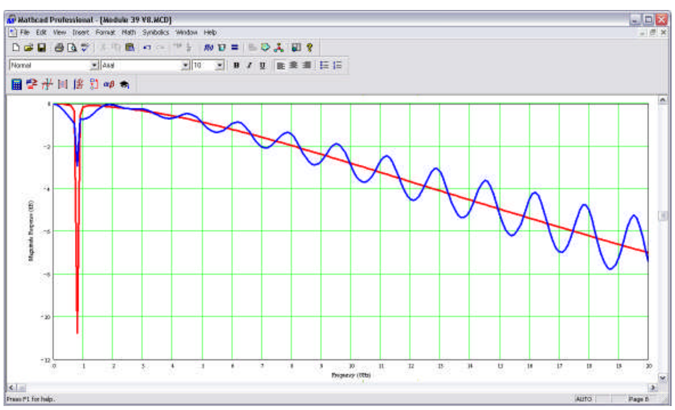

Fig. 2. $S_{21}(f)$ transfer functions when *X=40mils* and *Y=100mils* without reflections (red), and when only considering the first three reflections between the source and the cutout (blue). In this case, the notch frequency occurs at about 0.85GHz. The capacitance of the stitching capacitor is 20pF.

Figure 2 shows that a notch occurs in this frequency response. The location of this notch frequency is about 0.85GHz. The strength of the notch is only about 11dB, and is also reasonably narrow. Figure 3 shows the resulting output eye pattern from this situation.

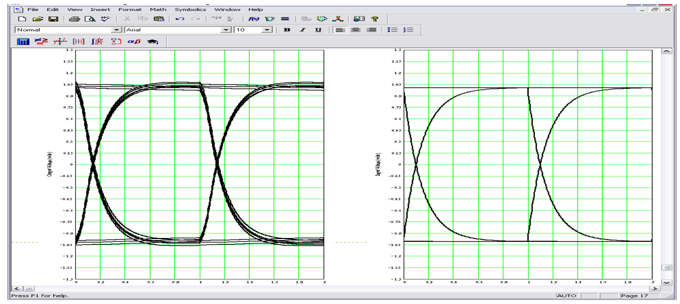

Fig. 3. Output 10Gbs eye pattern (left) and the reference input 10Gbs eye pattern (right). The risetime of the input signal is 40ps. The capacitance is 20pF.

Figure 4, on the other hand, shows the output eye pattern when two identical reference plane cutouts are encountered somewhere along the propagation path, in which *X=40mils* and *Y=100mils* for both cutouts. In this situation, the second identical cutout caused a reduced noise margin, as well as increased timing jitter.

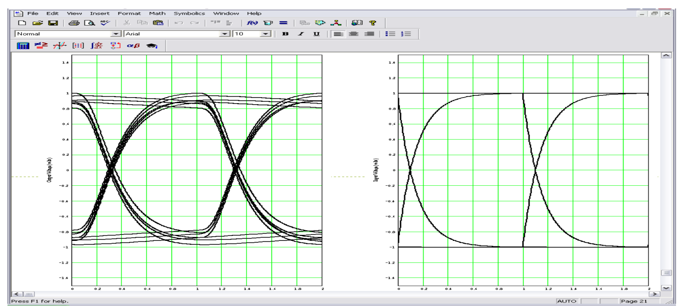

Fig. 4. Output 10Gbs eye pattern (left) and the reference input 10Gbs eye pattern (right). The risetime of the input signal is 40ps. The capacitance is 20pF.

If the capacitance is increased to 100pF for the case of two identical cutouts in which *X=40mils* and *Y=100mils*, which is the limit in which 0201 capacitors can be used for this application, then Fig. 5(a) shows the output eye pattern. Figure 5(b) shows the $S_{21}(f)$ forward transfer function from 0Hz up to 40GHz. Note that the 100pF capacitance caused the elimination of any kind of notch in the $S_{21}(f)$ function.

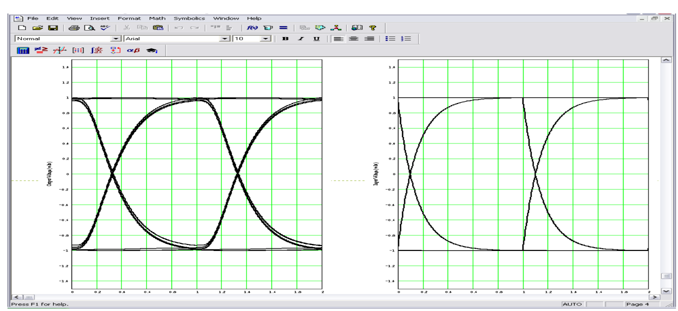

Fig. 5(a). Output 10Gbs eye pattern (left) and the reference input 10Gbs eye pattern (right). The risetime of the input signal is 40ps. The capacitance is 100pF.

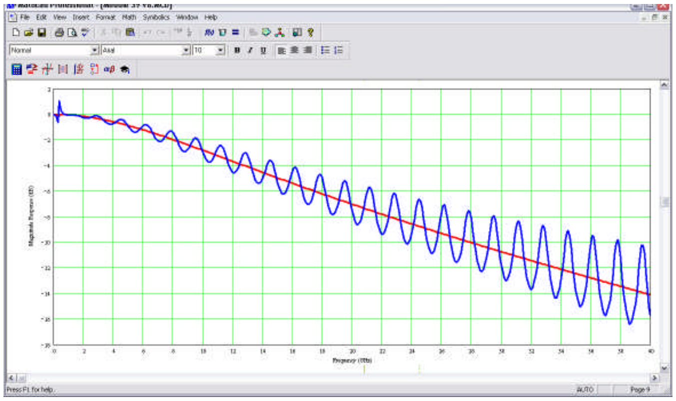

Fig. 5(b). $S_{21}(f)$ transfer functions when *X=40mils* and *Y=100mils* without reflections (red), and when only considering the first three reflections between the source and the cutout (blue). In this case, there is no notch in this frequency response. The capacitance of the stitching capacitor is 100pF.

From Fig. 5(a), it is clear that 100pF is sufficient for minimizing the output timing jitter, while maximizing the output noise margin. Figure 6 shows the situation in which two larger cutouts, in which *X=40mils* and *Y=200mils*, are encountered somewhere along the propagation path. As can be seen from Fig. 6, the output eye pattern is virtually unchanged from that shown in Fig. 5(a). This result is mostly due to the fact that more current returns through the 100pF capacitance due to its smaller impedance relative to the impedance from the inductance of the cutout. Based upon Figs. 3-6, 0201 100pF capacitors are sufficient for generating excellent signal integrity performances for two identical cutouts.

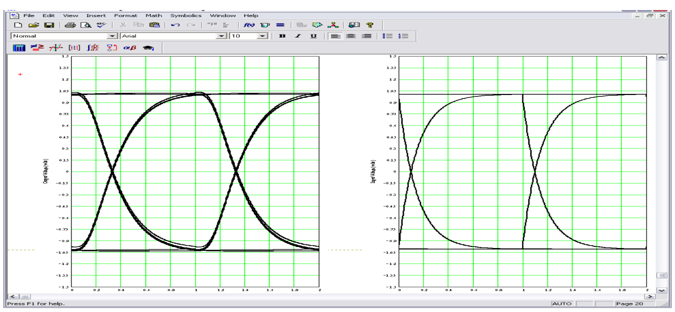

Fig. 6. Output 10Gbs eye pattern (left) and the reference input 10Gbs eye pattern (right). The risetime of the input signal is 40ps. The capacitance is 100pF, and *X=40mils* with *Y=200mils* for the two identical cutouts.

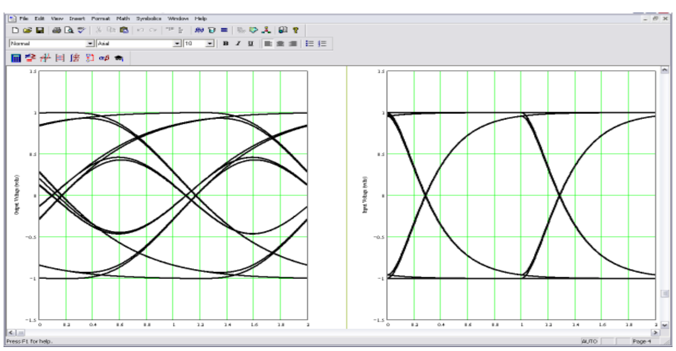

Fig. 7. Output 10Gbs eye pattern (left) and the reference input 10Gbs eye pattern (right). The risetime of the input signal is 40ps, and *X=40mils* with *Y=200mils* for the two identical cutouts. There are no stitching capacitors.

It is expected that larger cutouts will not induce any further signal integrity degradations with 100pF stitching capacitors. For reference purposes, Fig. 7 shows the output eye pattern without any stitching capacitors, and with *X=40mils* and *Y=200mils* for the two identical cutouts. Note that the noise margin is significantly reduced without stitching capacitors. Figure 8 shows the case in which two identical cutouts with *X=40mils* and *Y=30mils* are encountered somewhere along the propagation path with 100pF stitching capacitors. It appears that 100pF stitching capacitors are all that are needed in order to produce very good signal integrity performances when two identical, small cutouts are encountered somewhere along the propagation path. Whether the two identical cutouts are large or small, 100pF capacitors are sufficient for producing good signal integrity performances. This result is important because it allows the use of very small 0201 capacitors, therefore minimizing the needed printed circuit board real estate for this application.

Figure 9 highlights the case in which four identical cutouts are encountered somewhere along the propagation path, in which *X=40mils* and *Y=30mils* for each cutout. In this case, the noise margin is reduced and the timing jitter is slightly increased in value. Although there is a reduction in the noise margin for this situation, the output eye pattern is still very good in the sense that it should produce a zero bit-error-rate. For reference purposes, Fig. 10 shows the output eye pattern without any stitching capacitors for the same four identical cutouts. Figure 10 shows that the noise margin is reduced by about 37% without any stitching capacitors, and the timing jitter is slightly increased.

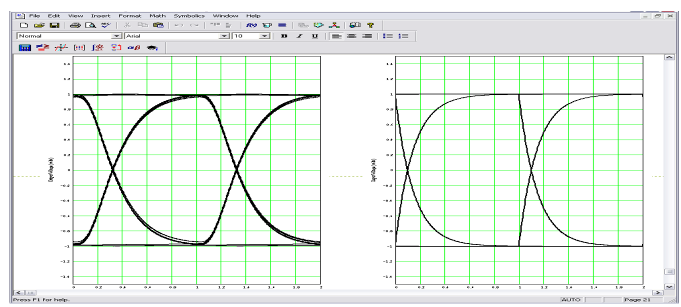

Fig. 8. Output 10Gbs eye pattern (left) and the reference input 10Gbs eye pattern (right). The risetime of the input signal is 40ps. The capacitance is 100pF, and *X=40mils* with *Y=30mils* for the two identical cutouts.

The number of identical cutouts needed in order to significantly close the output eye pattern is shown in Fig. 11(a), in which ten identical cutouts lie somewhere along the propagation path. Although encountering ten identical cutouts is not very likely, it is still instructive to note the signal integrity performance degradations with this number of small, identical cutouts. Figure 11(b) highlights the situation in which the stitching capacitance has been increased from 100pF to 470pF for the ten cutouts. As can be seen from Fig. 11(b), the additional capacitance decreases the timing jitter, while also increasing the noise margin. For reference purposes, Fig. 12 shows the output eye patterns without any stitching capacitors for this case. Figure 12 shows that the noise margin is reduced by about 75%, and is unacceptable.

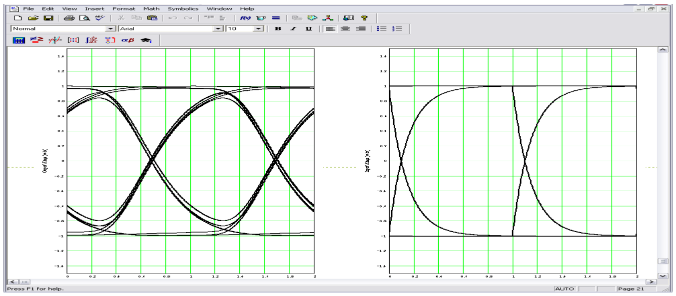

Fig. 9. Output 10Gbs eye pattern (left) and the reference input 10Gbs eye pattern (right). The risetime of the input signal is 40ps. The capacitance is 100pF, and *X=40mils* with *Y=30mils* for the 4 identical cutouts.

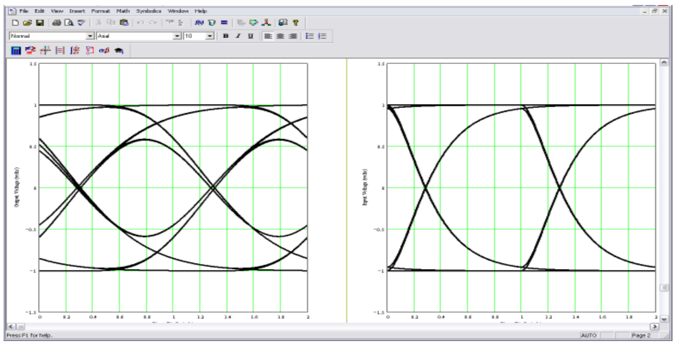

Fig. 10. Output 10Gbs eye pattern (left) and the reference input 10Gbs eye pattern (right). The risetime of the input signal is 40ps, and *X=40mils* with *Y=30mils* for the 4 identical cutouts. There are no stitching capacitors.

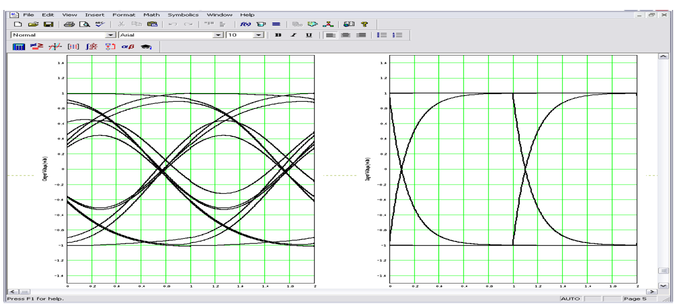

Fig. 11(a). Output 10Gbs eye pattern (left) and the reference input 10Gbs eye pattern (right). The risetime of the input signal is 40ps. The capacitance is 100pF, and *X=40mils* with *Y=30mils* for the 10 identical cutouts.

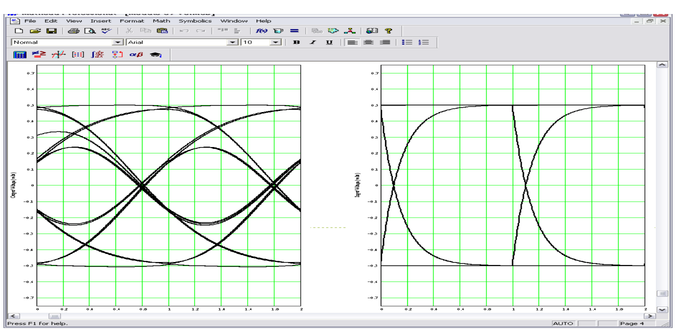

Fig. 11(b). Output 10Gbs eye pattern (left) and the reference input 10Gbs eye pattern (right). The risetime of the input signal is 40ps. The capacitance is 470pF, and *X=40mils* with *Y=30mils* for the 10 identical cutouts.

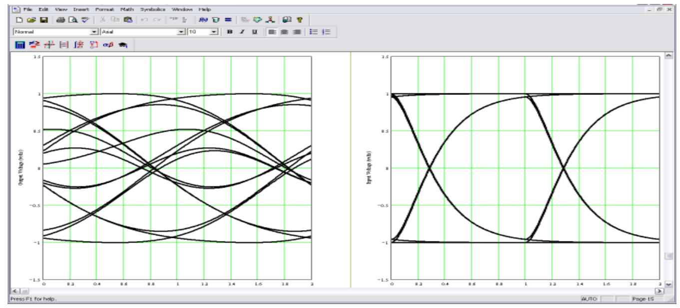

Fig. 12. Output 10Gbs eye pattern (left) and the reference input 10Gbs eye pattern (right). The risetime of the input signal is 40ps, and *X=40mils* with *Y=30mils* for the 10 identical cutouts. There are no stitching capacitors.

III. CONCLUSIONS

Based upon the previous research, it was disclosed that stitching capacitors can be used to help route return currents alongside their sources in order to mitigate signal integrity degradations on the high-speed propagating signal. It was shown how very small-valued stitching capacitors tend to induce small notches that occur in the $S_{21}(f)$ forward transfer function. It was then determined that 0201 100pF stitching capacitors were sufficient to mitigate the signal integrity degradations imposed by either small or large cutouts. By using 0201 100pF capacitors, the small 0201 package size can be used to minimize the printed circuit board real estate that is needed to place these capacitors on the board. In addition, it was demonstrated how increasing numbers of identical small cutouts can further degrade the signal integrity performance of the propagating signal by reducing the noise margins. However, it is not very likely in a practical layout of a printed circuit board for a high-speed signal to encounter a large number of cutouts. The material covered throughout this paper can studied through the interactive signal integrity learning environment that is available at the-signal-and-power-integrity-institute.com.