Practical Design Considerations for Dense, High-Speed, Differential Stripline PCB Routing Related to Bends, Meanders and Jog-outs
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Signal integrity rules of thumb are often not applicable

- Many rules originate from microwave and RF practices where packaging geometries may be far different from that used in dense high-speed digital systems
- Stripline bend design rules, the subject of this presentation, are one example (see examples on next slide)

**Rules of thumb state to use mitered bends rather than 90 degree corners**

- Or use arcs instead of a sharp point at any angle (overly-conservative for most applications)
- Lots of confusion on definition of ‘miter’
  - Many think of changing outside 90 corner to 45 degree slope as a miter – but that is a chamfer
  - Miter is actually a sloping joining face between joining objects
  - For our paper, a mitered bend is a 45 degree bend – two bends realize a 90 degree turn
PCB STRIPLINE SERPENTINE AND JOG-OUT EXAMPLES USED TO TUNE DIFFERENTIAL CHANNEL LENGTHS AND P/N LENGTHS, RESPECTIVELY
• Sharp outer corners not generally realizable
  – PCB design software mostly utilize gerber format
    • Stripline path is defined by circular aperture swept along path
    • Inner corner of 90 degree turn is sharp, outer corner has circular radius
• Measured results of striplines with differing bend structures were surprising
  – We wanted to determine better rules for restricting serpentine line usage
    • This is a hard problem; our results are by no means comprehensive but hopefully offer better guidance
  – We also wanted to utilize small bends (that are tolerable) to devise a method to make stripline length tuning easier
• Test board
  – Structure descriptions and measured results
  – Model comparisons to measurements

• Serpentine stripline structures
  – General periodic structure behavior
  – Serpentine structure descriptions
  – Electrical behavior of serpentine lines

• Back-jogs for length tuning within differential pair
  – Usage examples

• Summary
PCB BENDS

- Stripline bends in a PCB are required in several instances
  - Have to break-out of pin-fields to get to a routing channel
  - From/To pins are not lined up so have to implement bends/turns
  - Some nets require additional length to meet electrical timing requirements
    - These are meander or serpentine patterns – both have equivalent meaning
- For meander patterns, either minimize bends as much as possible with "trombone" patterns or add many more bends with "accordion" patterns
  - In practice, implementations may vary considerably depending on available routing area, personal preference, etc.
We designed 12" patterns with both trombone and accordion patterns and with both 90 degree and mitered bends (a 90 degree turn using two 45 degree turns)

- Trombone pattern had just one down-and-back pattern
- Accordion pattern had 34 serpentine patterns, 136 bends + 1 more for entry into probe pads
- Patterns repeated 3 times to determine uniformity

Board used low-loss Isola FR408 (Er=3.65, loss-tan=0.01) and tight 3313 weave (to minimize fiber-weave-skew)

Striplines, all differential, were 5 mil wide with 10 mil space

Dielectric thickness ~5 mils used to obtain ~100 ohm-differential impedance

Used high bandwidth G-S-G-G-S-G microwave probes
SERPENTINE STRIPLINE TEST STRUCTURES USED TO DETERMINE EFFECTS OF STRIPLINE BENDS
(Both 90 Degree Corner and 45 Degree Mitered Bends Implemented;
Trombone Style has 14 Bends; Accordion Style has 137 Bends)
PCB TEST STRUCTURES – MEASURED RESULTS

• Accordion patterns have noticeable sharp insertion loss drop-outs at 17.5 GHz
  – About 7 and 2.5 dB for 90 and 45 degree bends, respectively
• Measurements across three patterns are fairly consistent through ~18 GHz
• We also took X-ray images of our bends
  – It is possible that PCB vendors augment design to remove sharp corners (to avoid acid traps)
  – Sharp corners (by design) may be etched away to some degree
  – PCB software may not actually produce outer sharp corners, e.g., Gerber format produces corners with circular arcs
• Our 90 degree bends have under-etched inner corners and circular arcs for outer corners
MEASURED ELECTRICAL INSERTION LOSS PERFORMANCE OF SERPENTINE DIFFERENTIAL STRIPLINES

(12 Inch Lines; 0.005" Wide, 0.010" Space Differential Striplines; 3313 Weave Isola FR408HR Laminate)

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**34 "Accordion" Identical Serpentine**

(137 Bends)

**1 "Trombone" Serpentine**

(14 Bends)

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- **90° Bends SDD21, dB**
- **45° Mitered Bends SDD21, dB**

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Frequency, GHz

Frequency, GHz
X-RAY IMAGES OF PRINTED CIRCUIT BOARD DIFFERENTIAL STRIPLINE - 90 DEGREE VERSUS MITERED BENDS

90 Degree Bends

45 Degree Mitered Bends
• We created 3-D full-wave EM model of accordion-style structures
  – Both for 90 and 45 degree bends
  – Just model 1 of 34 structures and mathematically chain to realize model of complete structure
  – Use manufacturer’s laminate specifications for electrical parameters, we then adjust surface roughness to match our measured insertion losses
• Simulated insertion loss drop-outs are at correct frequency but lower magnitude than that measured
  – 4 vs. 7 dB and 1.5 vs. 2.5 dB
• Simulations do not show minor resonances
  – We believe ground stitching vias / planar cavities cause these
HFSS DIFFERENTIAL STRIPLINE MODELS AND SIMULATED RESULTS OF 90 DEGREE VERSUS TWO 45 DEGREE BENDS

( Modeled S-Parameters are Mathematically Cascaded Together 34 Times to Represent 34 Repeating (Identical) Structures )
• Test board
  – Structure descriptions and measured results
  – Model comparisons to measurements

• **Serpentine stripline structures**
  – General periodic structure behavior
  – Serpentine structure descriptions
  – Electrical behavior of serpentine lines

• Back-jogs for length tuning within differential pair
  – Usage examples

• Summary
We realize that our PCB bend structures are periodic
  - Actual repeating structure is one-half of serpentine structure, e.g.,
  we have 68 repeating structures for 34 serpentines

Simple circuit used to approximate our 34-structure with 90 degree bends
  - 68 lossy transmission lines with 15 fF capacitors between them to match measured 9 dB drop-out at 17.5 GHz

Periodic electrical behavior affected by several factors
  - Small down-and-back reflections get multiplied by N(=68) patterns
  - Sharp drop-outs occur at half wave-length multiples
  - Reactances grow at higher frequencies which increase drop-out magnitudes
  - Transmission line loss increases with frequency to decrease drop-out magnitudes
BEHAVIOR OF PERIODIC STRUCTURES CHAINED TOGETHER WITH LOSSY PCB STRIPES (Insertion Loss Drop-Outs Occur At One-Half Wavelength Intervals Increasing In Magnitude With Increasing Frequency)

Lossy models, 50Ω 0.1774", $\varepsilon_r = 3.65$

![Diagram of periodic structures with lossy models and frequency response graph showing S21 and S11 in dB vs. frequency in GHz.](image-url)
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• Summary
• Serpentine examples
  – Periodic, up to 7 identical meander patterns (14 periodic structures)
    • These can come from copying patterns or auto-generated by PCB software
  – Note that longer meander patterns will cause resonances at lower frequencies

• Jog-out examples
  – In-line pin-field escape causes differential pair mismatch equal to pin-field pitch (1 mm in this case)
  – Typically require many jog-outs to equalize line lengths
  – We’ve assumed loosely-coupled striplines – additional problems if tightly coupled
PCB STRIPLINE SERPENTINE AND JOG-OUT EXAMPLES USED TO TUNE DIFFERENTIAL CHANNEL LENGTHS AND P/N LENGTHS, RESPECTIVELY
• Test board
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• Summary
SERPENTINE STRUCTURE EXAMPLES

• Changing number of serpentines with fixed stripline length
  – We do see the half-wave (1st) resonance at the expected frequency
  – The higher order resonances are small or nonexistant
    • Possibly due to fact that repeating pattern has two discontinuities within repeating pattern
    • Also capacitance is distributed rather than lumped

• Adjacent structure spacing
  – Here we do see resonance magnitude increase in higher order harmonics
  – Our model captures only 11 of 23 coupled regions (24 meander patterns in 12“ total length)

• Varying stripline width can greatly increase resonance magnitude
  – Larger discontinuity and lower stripline loss both act together
  – Again, higher frequency resonances are missing
EFFECT OF INCREASING NUMBER OF SERPENTINE PATTERNS PER UNIT LENGTH OF DIFFERENTIAL PCB STRIPLINE
(Line Lengths Held Constant at 1" for Each 3-D Model; Resulting S-Parameters Mathematically Chained to Represent 12" Equivalent Stripline Length, 5 / 15 mil Stripline Width Spacing)

1 Serpentine per Inch

2 Serpentes per Inch

3 Serpentes per Inch

\[ d = 60 \text{ mils} \]
\[ m: \text{Models de-embedded to these boundaries} \]

12 x Chained S-Parameters

Serpentines per Inch
- 1
- 2
- 3

Frequency, GHz

0
5
10
15
20
25
30

0
-5
-10
-15
-20
-25
-30
-35
EFFECT OF DECREASING PITCH BETWEEN DIFFERENTIAL PCB STRIPLINE SERPENTINE PATTERNS

(Line Lengths Held Constant at 1" for Each 3-D Model; Resulting S-Parameters Mathematically Chained to Represent 12" Equivalent Stripline Length, 5 / 15 mil Stripline Width/Spacing)

$s = 37.5$ mils
$s = 25.0$ mils
$s = 17.5$ mils
$s = 10.0$ mils

$d = 60$ mils
$m$: Models de-embedded to these boundaries
$s$: Spacing

**Graphs:**
1. **12 x Chained S-Parameters**
   - Frequency, GHz
   - SDD21, dB
   - Spacing (mils): 10.0, 17.5, 25.0, 37.5
2. **SDD11, dB**
   - Frequency, GHz
   - Frequency, GHz
   - NOV. 05 / 2013 / MJD / 44277
   - MAYO CLINIC SPPDG

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EFFECT OF INCREASING L INEWIDTH OF DIFFERENTIAL PCB STRIP LINE SERPENTINE PATTERNS
(Line Lengths Held Constant at 1" for Each 3-D Model; Resulting S-Parameters Mathematically Chained
to Represent 12" Equivalent Stripline Length, 5 / 15 mil Stripline Width/Spacing)

3 mils Wide Striplines
5 mils Wide Striplines
7 mils Wide Striplines

\[ d = 60 \text{ mils} \]
\[ m: \text{Models de-embedded to these boundaries} \]

**Stripline Width (mils)**
- 3
- 5
- 7

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SDD21, dB

**SDD21, dB**

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Typically, meandering lines should not have performance impacts

- But there are some risk areas

Lower risks by

1. Use mitered versus 90 degree bends
2. Use fewer longer (trombone) versus many shorter (accordion) serpentine patterns
3. Don’t use repeating patterns – even small length adjustments could be beneficial
4. Don’t crowd adjacent patterns too tightly
5. Be especially careful with wide lines (> 0.005“)
OUTLINE

• Test board
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• Summary
CORRECTING PIN-FIELD SKEW WITH BACK-JOGS

• We observe that a few stripline bends generally will not cause problems

• Use this result to try to reduce or eliminate jog-outs
  – Essentially route backward jog-outs, i.e., a back-jog to minimize pin-field skew

• Standard break-outs are 45 degree paths toward outside of pin-field to reach routing channel between pin columns
  – Back-jog uses three bends with three equal length short segments to reach between pin columns
    • This is our approach – other variations may be possible
    • With shorter path backing up toward complement pin resulting baseline (maximum) skew is 0.707*pin-pitch
    • Slide p/n striplines closer together to further reduce skew
    • Minimum skew is dependant on pin-pitch and stripline width
PROPERTIES OF BACK-JOG PIN-FIELD STRIPLINE ESCAPE WITH RESPECT TO DIFFERENTIAL PAIR TUNING
(Back-Jogs can Reduce or Eliminate Need for Conventional Jog-Outs to Match Differential Pair Lengths)

Maximum Pinfield Skew (No Vertical Back-Jogs)

Pinfield Skew = \( \frac{P'}{\sqrt{2}} = 0.707 \)

Maximum Tuning (Allows Stripline Spacing (m) to be ≥ Stripline Width (w))

2\(^*j = 0.715 \) which is greater than back-jog pin-field skew (0.707)

Standard In-Line Breakout

Pinfield Skew = \( P' = 1.000 \)

Pinfield Skew Set To Zero Out Mitered Turn

2\(^*j = 0.707 - 0.400 \)

j = 0.154

Corner Skew = 4\(^*p^*\tan 22.5^\circ = 0.400 \)

Line width = 4 mils, Pin Pitch = 1 mm for all examples

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SPPDG

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MAXIMUM STRIPLINE LENGTH TUNING CAPABILITY FROM BACK-JOGS OF DIFFERING PIN PITCHES AND STRIPLINE WIDTHS

(Back-Jog Length Tuning Limited By Proximity of Differential Pair Signal Paths; Limit Arbitrarily Set Such That Minimum Spacing is Set to Line Width)

[1] Stripline minimum spacing arbitrarily set to stripline width

Striplines that are sufficiently narrow can de-skew pin-field skew
• We simulated a standard versus back-jog pin-field escape
  – Assumes 100 mil thick PCB and 10 mil diameter vias having 13 mil via stub, 26x65 mil oblong antipads
• Back-jog has somewhat higher return loss but lower frequency-dependant skew
  – Based on previous work, we believe that augmenting the antipad shape can reduce back-jog return loss
ELECTRICAL PERFORMANCE OF STANDARD IN-LINE VERSUS BACK-JOG PIN-FIELD BREAKOUT
(In-Line Approach Requires Jog-Out to Match Differential Pair Lengths;
Back-Jog Can Cancel Out Skew Within Pin-Field)

In-Line Model

Back-Jog Model

3 mil wide striplines, 1 mm pin pitch, 13 mil via stub, 100 mil board thickness

Differential S-Parameter Losses

Differential Path Skew Through Model

TDR Response

-40 -35 -30 -25 -20 -15 -10 -5 0
Loss, dB

0 5 10 15 20 25 30 35 40
Frequency, GHz

-10 -5 0 5 10
Time, psec

0.5 0.6 0.7 0.8 0.9 1.0 1.2 1.3 1.5
Normalized to 1 Volt, Volts

0 40 80 120 160 200 240 280 320
Time, psec

In-Line Model
Back-Jog Model

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• Summary
It is difficult to manually lay out back-jogs in our PCB software
  - Instead we automate using (Cadence) SKILL program
Examples assume 1 mm pin pitch, 3/6 mil width/spacing
Skew originates from pin-field break-out and bends
  - Skew equations in paper
  - Example shows that jog-outs can be reduced or eliminated versus standard (left-side) versus implementing back-jogs (right side)
COMPARISONS OF PCB DIFFERENTIAL STRIPLINE ROUTING USING TRADITIONAL IN-LINE ROUTING PIN-FIELD ESCAPE VERSUS USING BACK-JOG PIN-FIELD ESCAPE
(Back-Jogs Greatly Reduce the Requirement for Jog-Outs Needed to Equalize Skew from Pin-Field Escape and Stripline Turns)
SUMMARY

- Meandering lines not expected to be problematic for data-rates up to 10 Gb/s
  - Be more diligent for higher data-rates
- To reduce risk, use mitered bends and avoid high numbers of ‘perfectly’ repeated patterns
- Be careful when using wider striplines
- Don’t place adjacent serpentine patterns too closely
- Consider using back-jogs to eliminate or reduce jog-outs