DesignCon® 2014

Practical Design Considerations for Dense, High-Speed, Differential Stripline PCB Routing Related to Bends, Meanders and Jog-outs

January 28-31, 2014 | Santa Clara Convention Center | Santa Clara, CA

MAYO CLINIC

UBM Tech

AUTHORS

Michael J. Degerstrom, Mayo Clinic
degerstrom.michael@mayo.edu

Chad M. Smutzer, Mayo Clinic
smutzer.chad@mayo.edu

Dr. Barry K. Gilbert, Mayo Clinic
gilbert.barry@mayo.edu

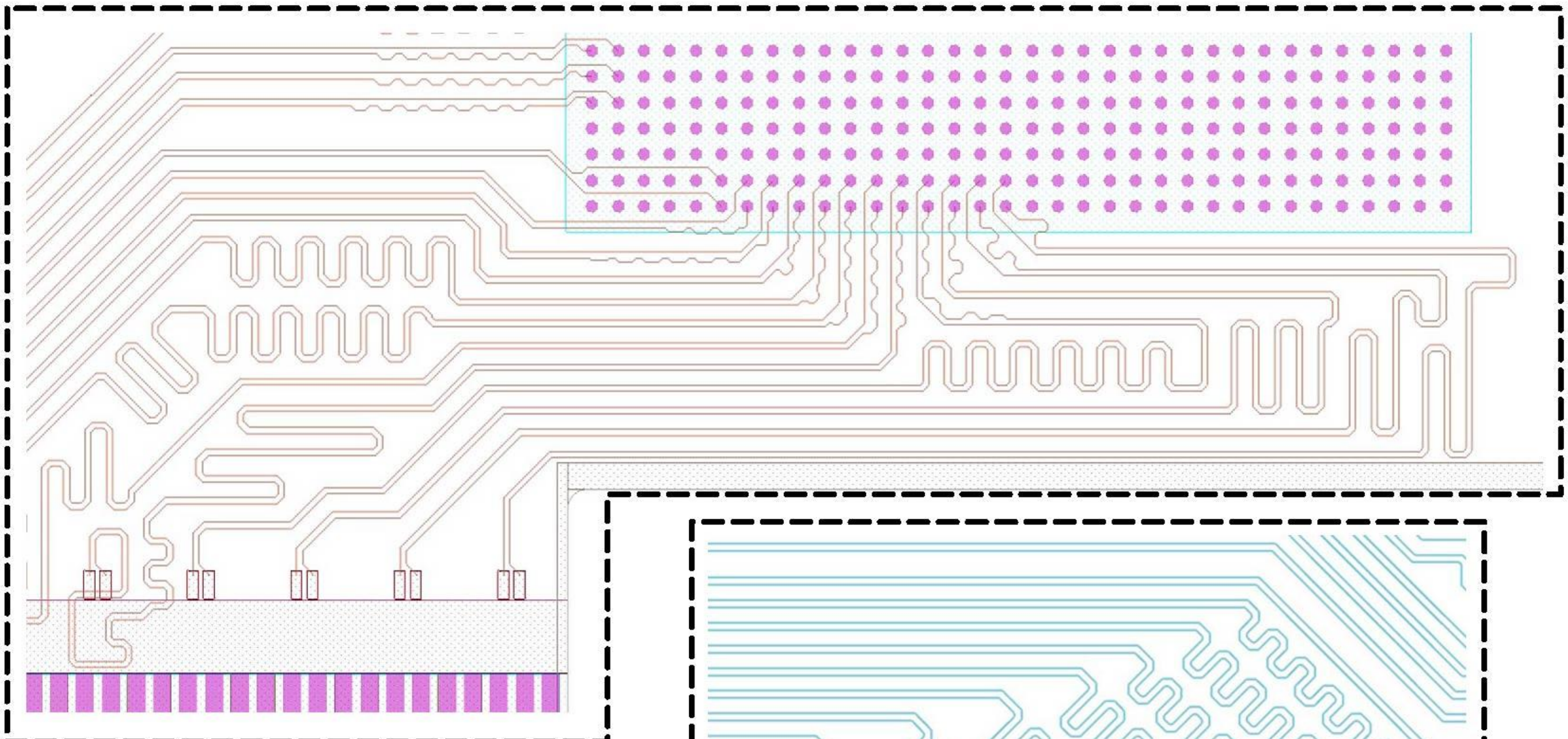
Dr. Erik S. Daniel, Mayo Clinic
daniel.erik@mayo.edu

INTRODUCTION - 1

- 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

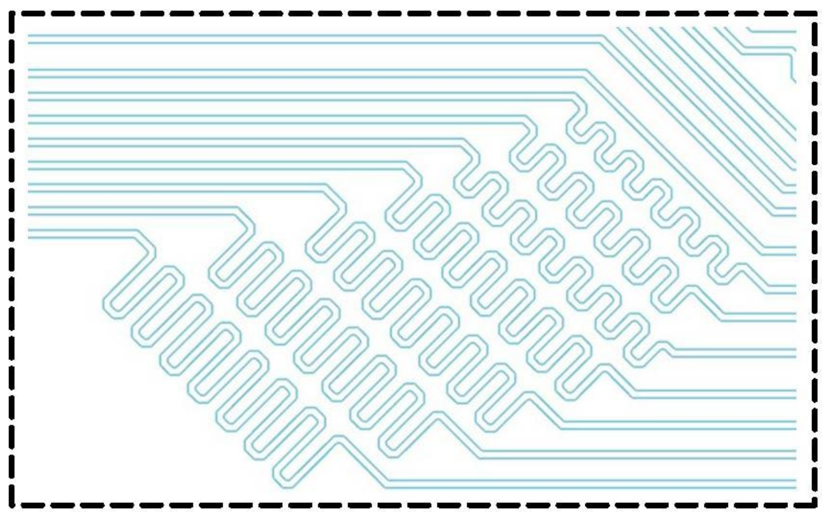
PCB STRIPLINE SERPENTINE AND JOG-OUT EXAMPLES USED TO TUNE DIFFERENTIAL CHANNEL LENGTHS AND P/N LENGTHS, RESPECTIVELY

Example #1



NOV_05 / 2013 / MJD / 44273

MAYO CLINIC SPPDG



Example #2

INTRODUCTION - 2

- 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

OUTLINE

- **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

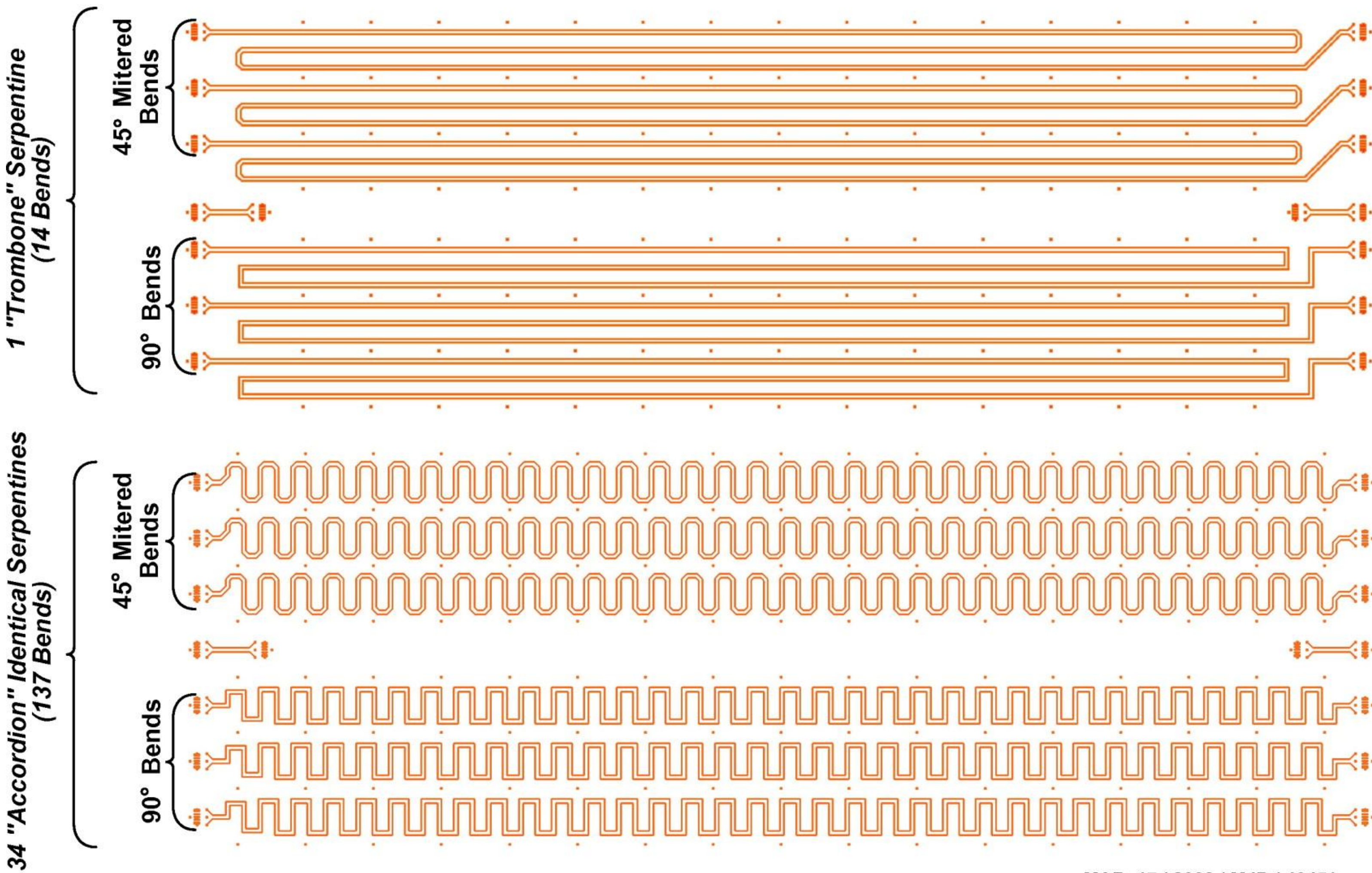
PCB BENDS

- 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.

PCB TEST STRUCTURES - DESCRIPTION

- 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)



MAR_17 / 2009 / MJD / 40451

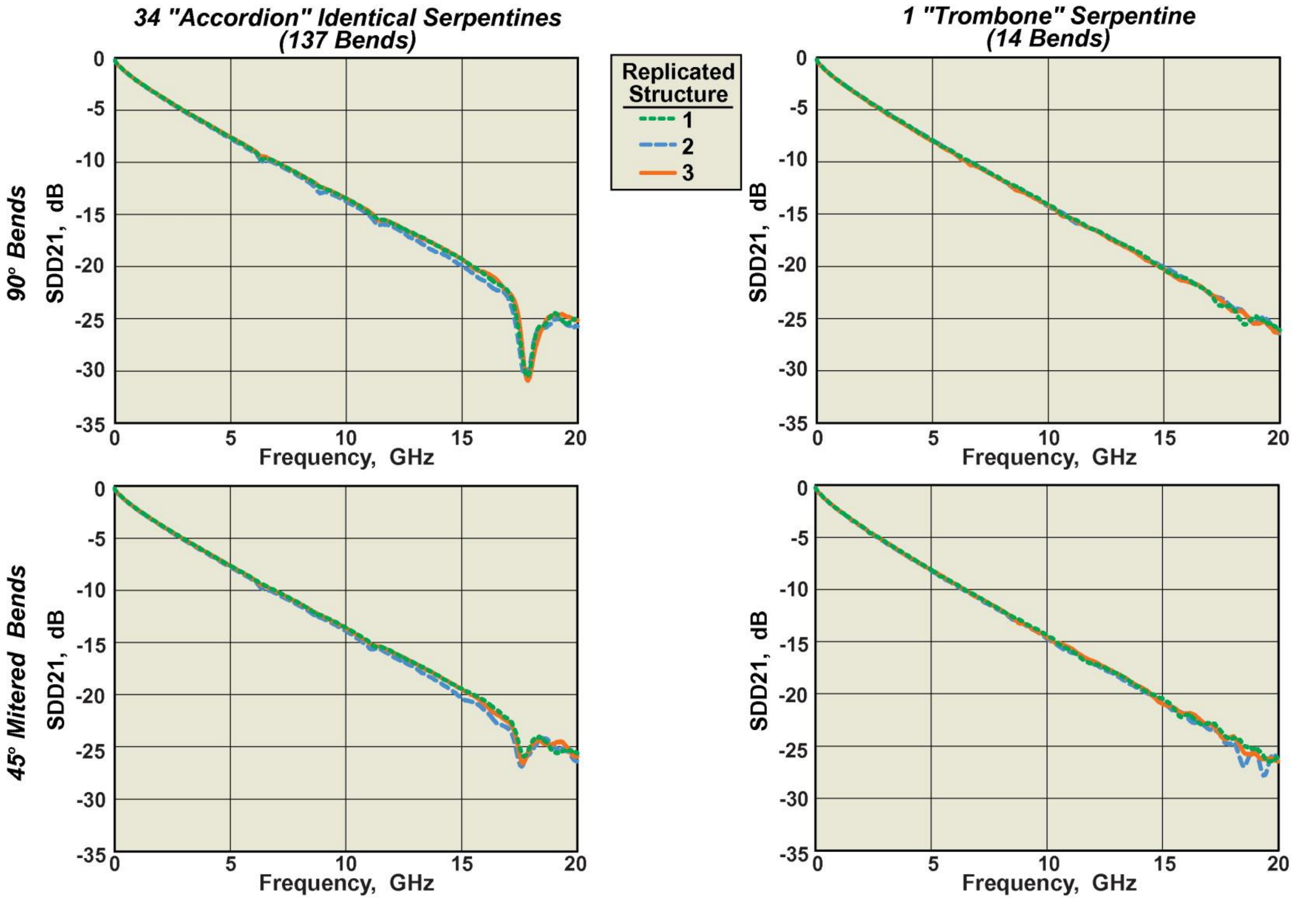
MAYO CLINIC
SPPDG

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 circulars 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)

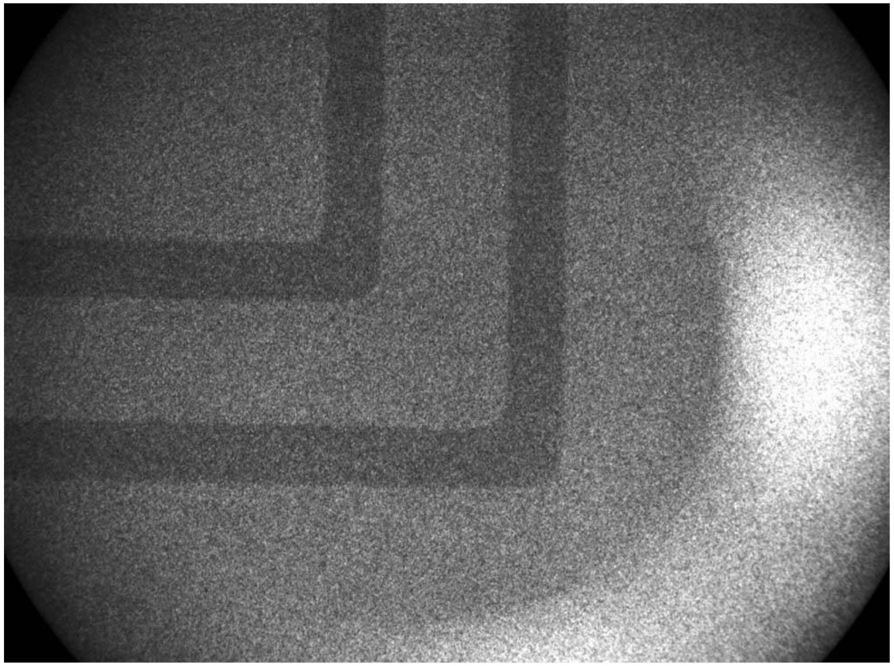


NOV_04 / 2013 / MJD / 44269

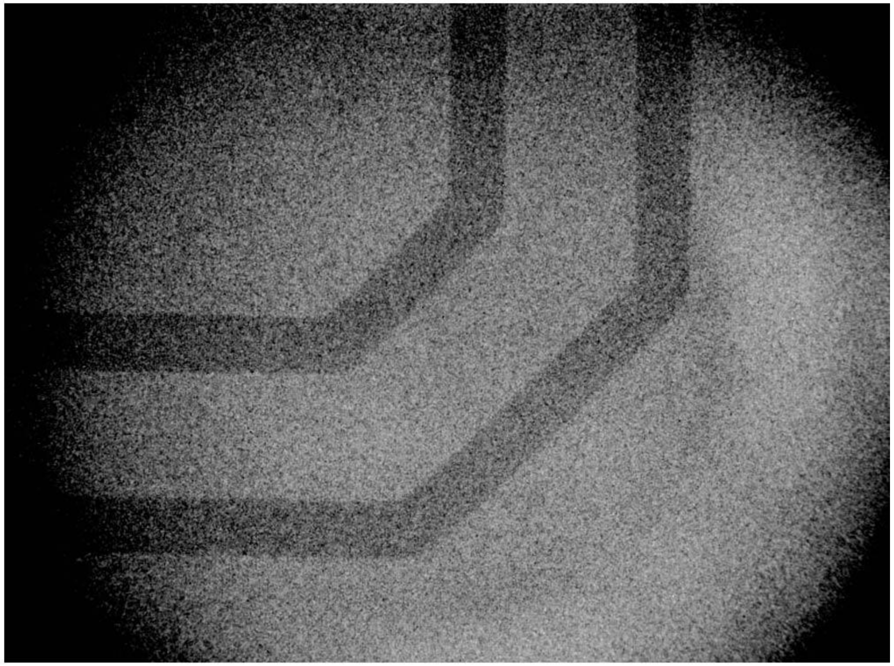
MAYO CLINIC
SPPDG

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

90 Degree Bends



45 Degree Mitered Bends



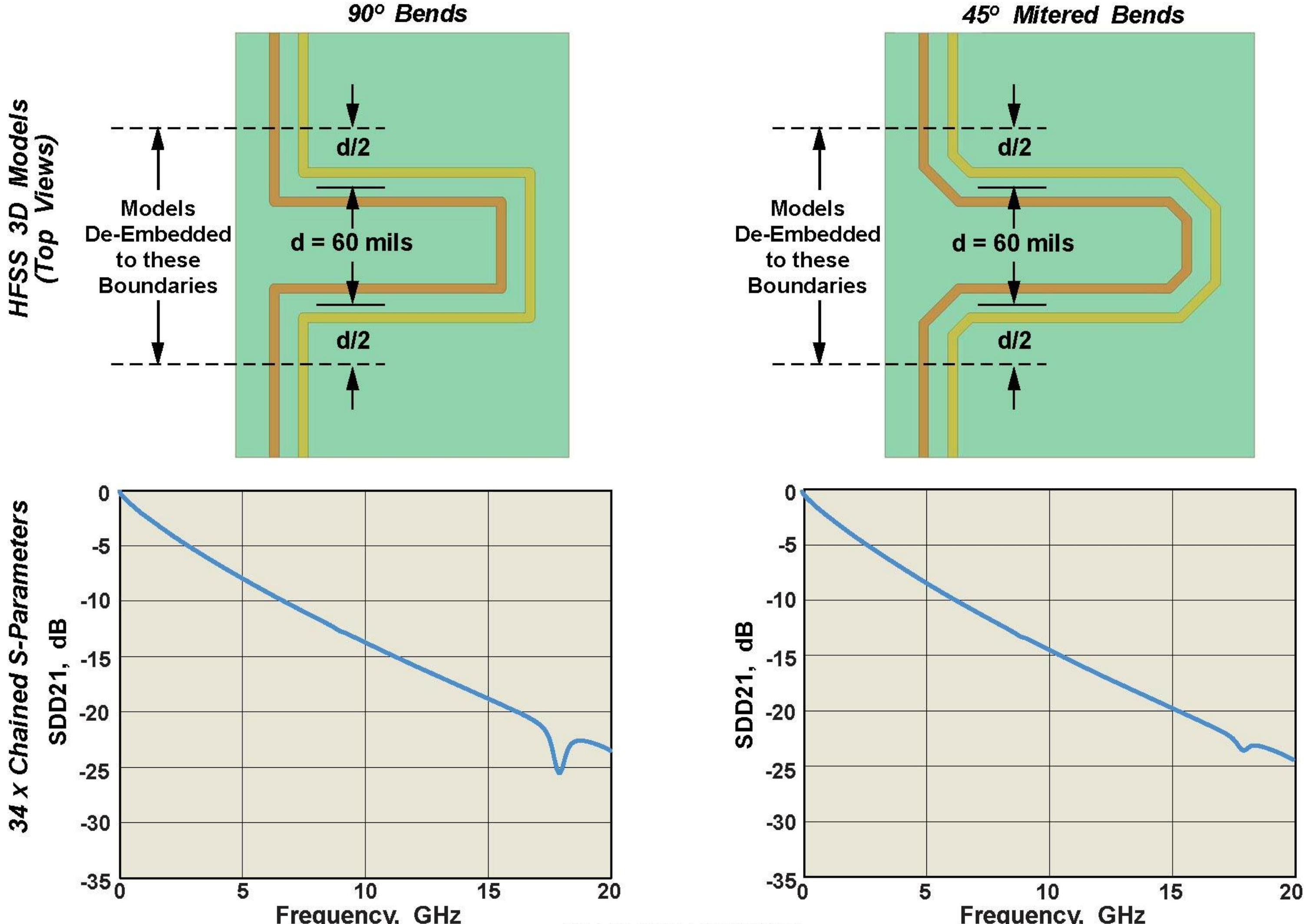
NOV_05 / 2013 / MJD / 44274

MAYO CLINIC
SPPDG

PCB TEST STRUCTURES – SIMULATION RESULTS

- 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)



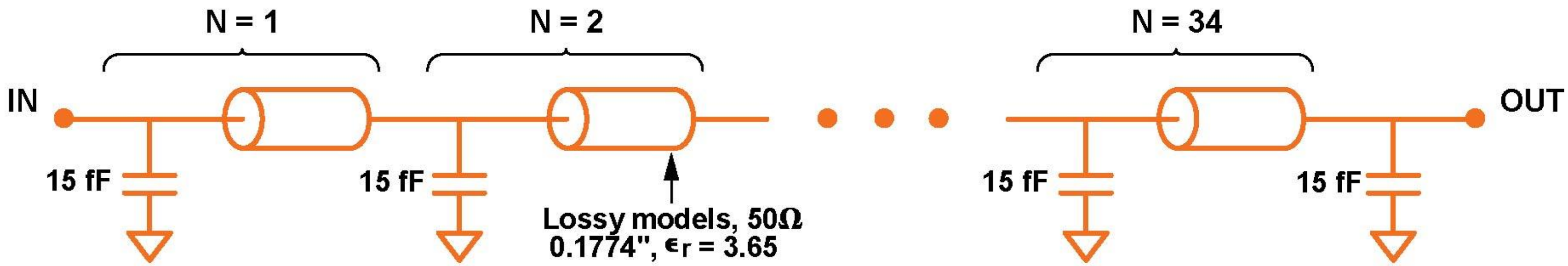
OUTLINE

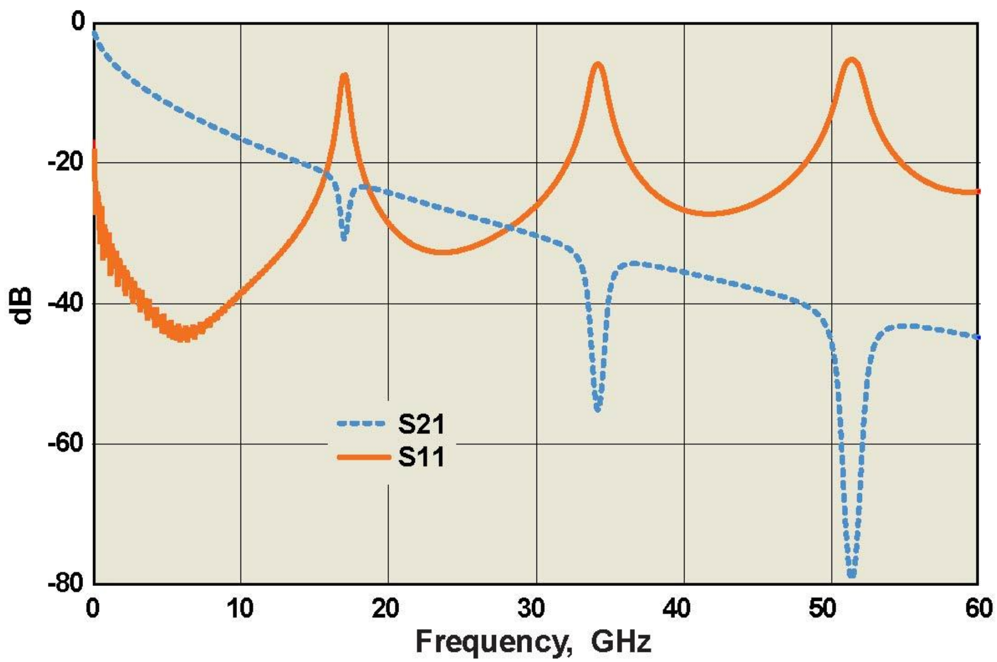
- Test board
  - Structure descriptions and measured results
  - Model comparisons to measurements
- **Serpentine stripline structures**
  - **General periodic structure behavior**
  - Serpentine structure descriptions
  - Electrical behavior of serpentine lines
- Back-jogs for length tuning within differential pair
  - Usage examples
- Summary

BEHAVIOR OF PERIODIC STRUCTURES

- 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 STRIPLINES
(Insertion Loss Drop-Outs Occur At One-Half Wavelength Intervals Increasing In Magnitude With Increasing Frequency)





NOV_05 / 2013 / MJD / 44271
MAYO CLINIC
SPPDG

OUTLINE

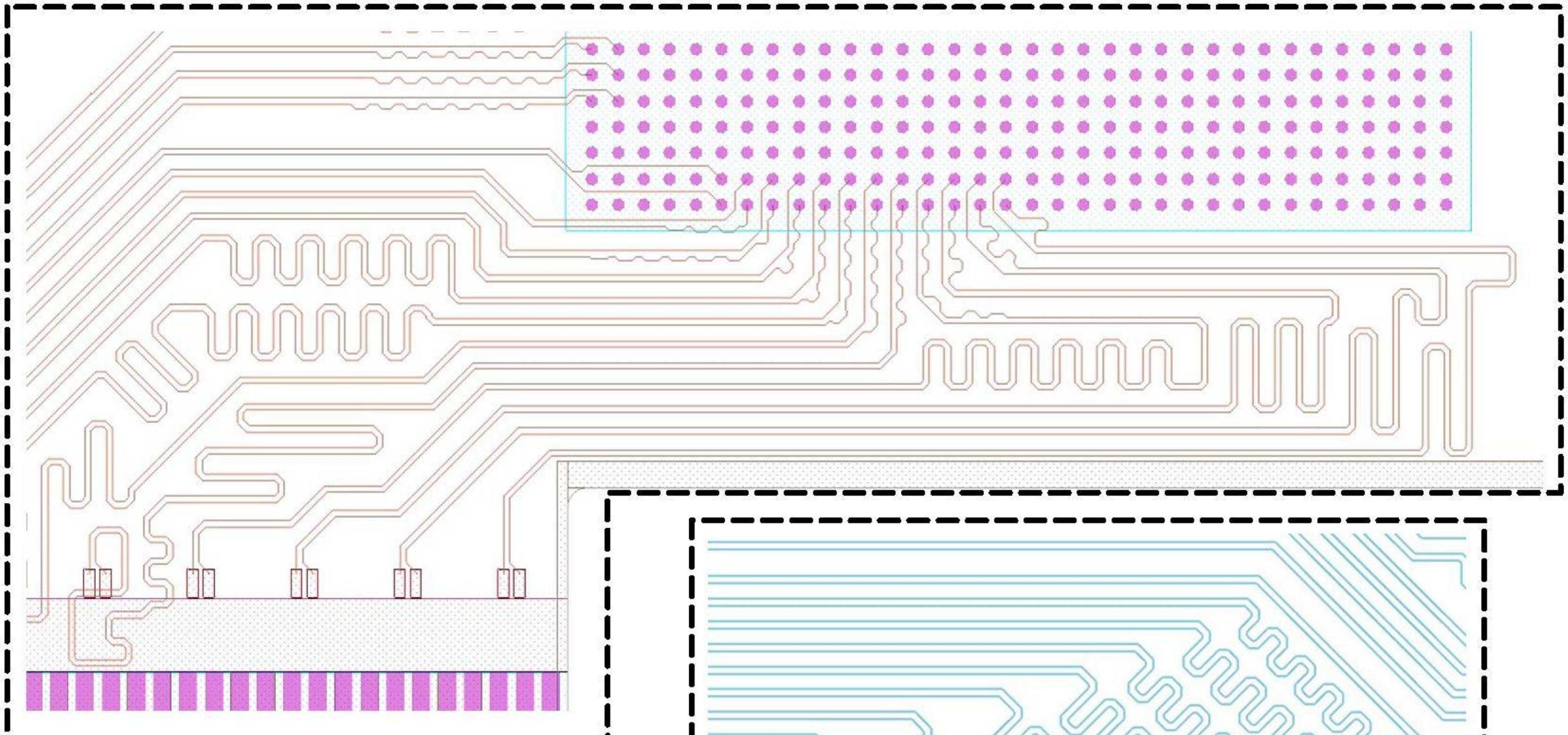
- Test board
  - Structure descriptions and measured results
  - Model comparisons to measurements
- **Serpentine stripline structures**
  - General periodic structure behavior
  - **Serpentine structure descriptions**
  - Electrical behavior of serpentine lines
- Back-jogs for length tuning within differential pair
  - Usage examples
- Summary

SERPENTINE STRUCTURE DESCRIPTIONS

- 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

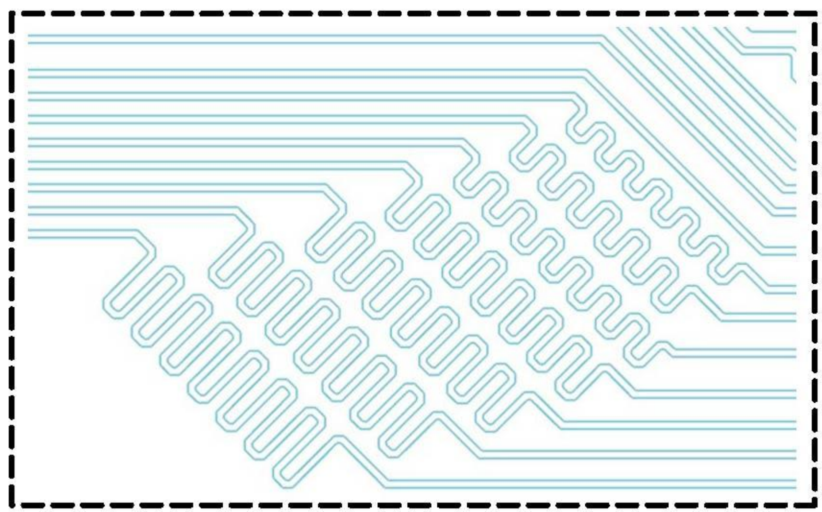
PCB STRIPLINE SERPENTINE AND JOG-OUT EXAMPLES USED TO TUNE DIFFERENTIAL CHANNEL LENGTHS AND P/N LENGTHS, RESPECTIVELY

Example #1



NOV_05 / 2013 / MJD / 44273

MAYO CLINIC SPPDG



Example #2

OUTLINE

- 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

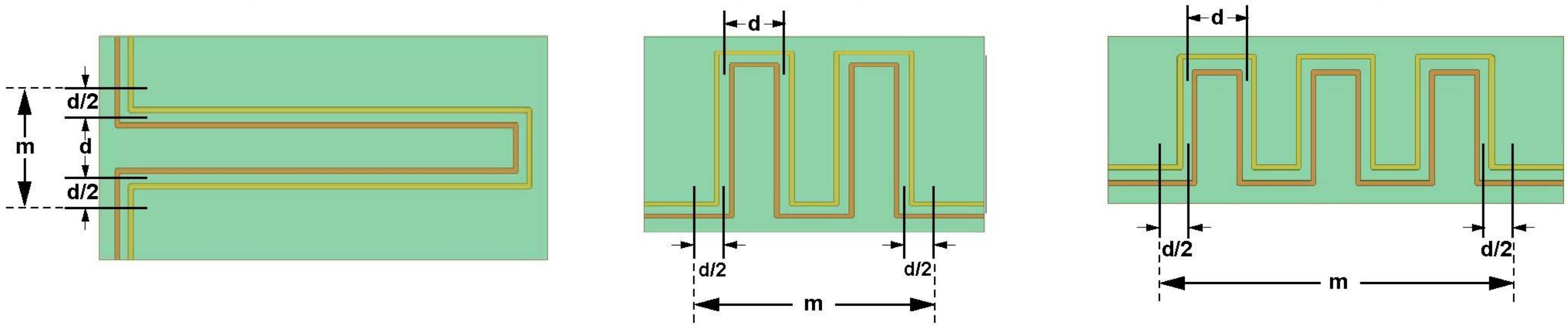
SERPENTINE STRUCTURE EXAMPLES

- Changing number of serpentines with fixed stripline length
  - We do see the half-wave (1st) resonance at the expected frequency
  - The higher order resonaces are small or nonexistant
    - Possibly due to fact that repeating pattern has two discontiuities 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

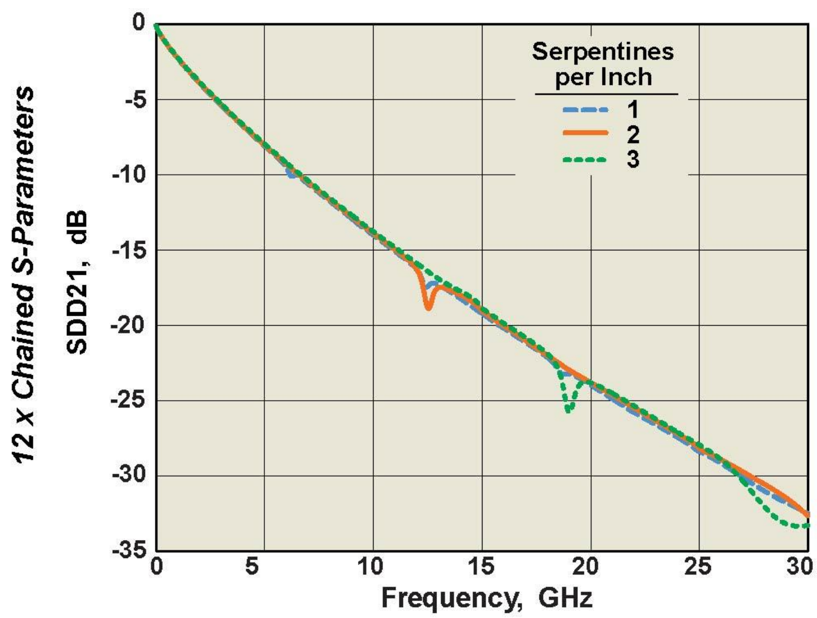
EFFECT OF INCREASING NUMBER OF SERPENTINE PATTERNS PER UNIT LENGTH OF DIFFERENTIAL PCB STRIPLINE

(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 Serpentines per Inch* — *3 Serpentines per Inch*



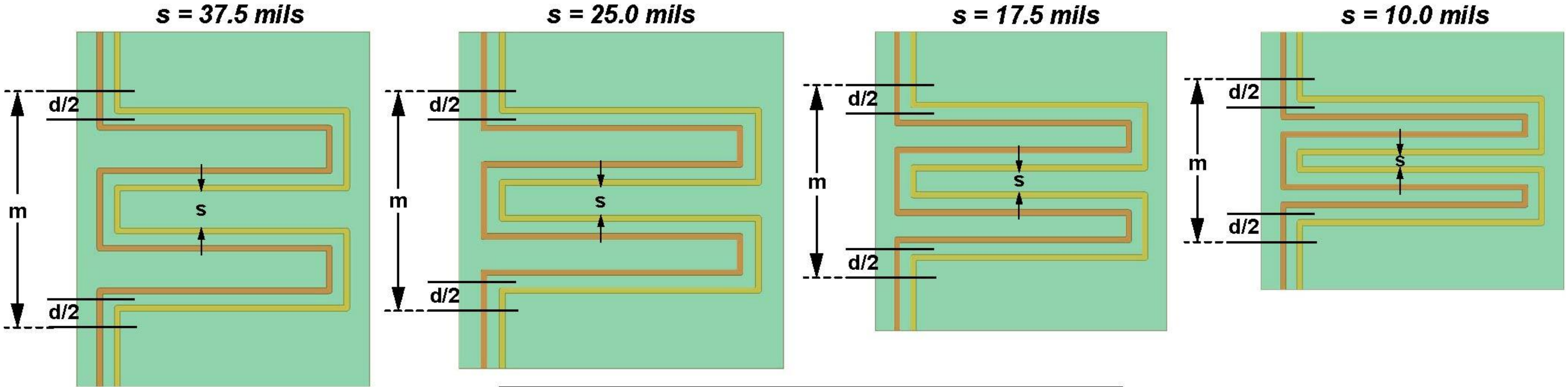
d = 60 mils
m: Models de-embedded to these boundaries



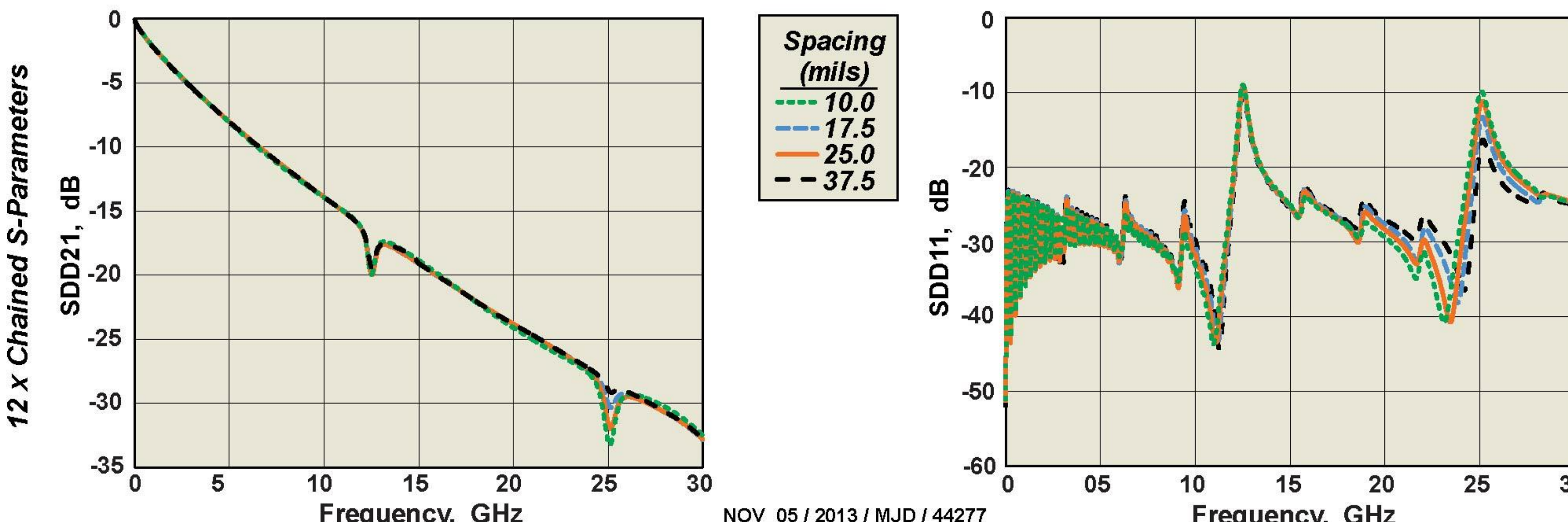
NOV_05 / 2013 / MJD / 44276
MAYO CLINIC
SPPDG

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)

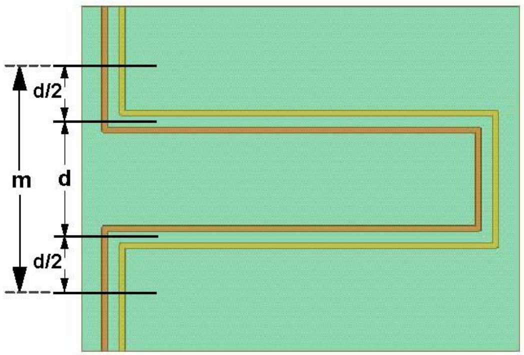


d = 60 mils
m: Models de-embedded to these boundaries
s: Spacing

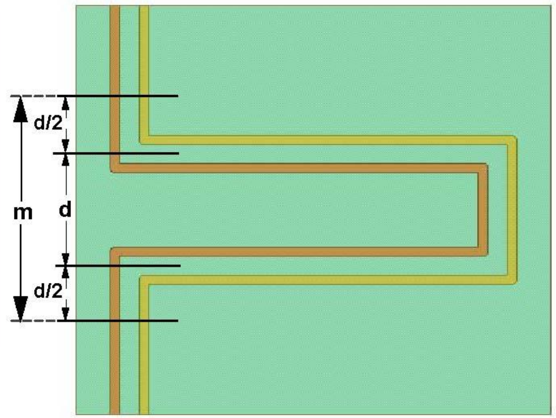


EFFECT OF INCREASING LINEWIDTH OF DIFFERENTIAL PCB STRIPLINE SERPENTINE PATTERNS
(Line Lengths Held Constant at 1" for Each 3-D Model; Resulting S-Parameters Mathematically Chained to Represent 12" Equivalent Stripline Length, 5 / 15 mil Stripline Width/Spacing)

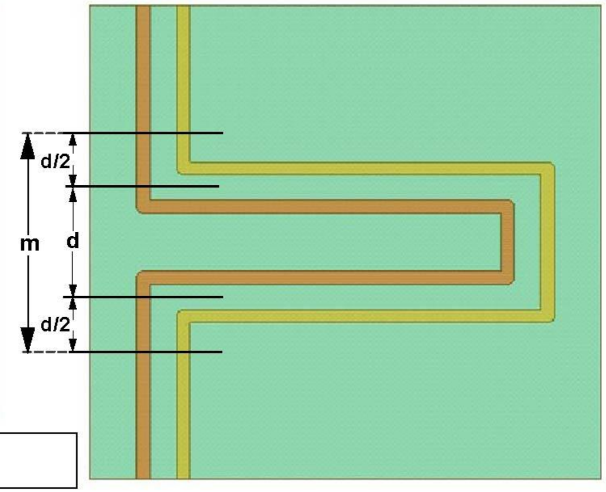
3 mils Wide Striplines



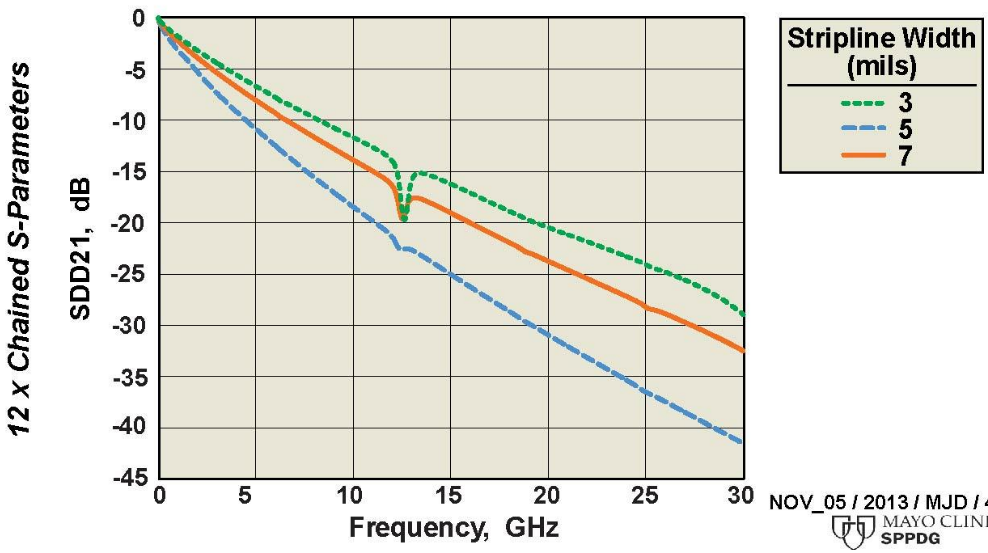
5 mils Wide Striplines

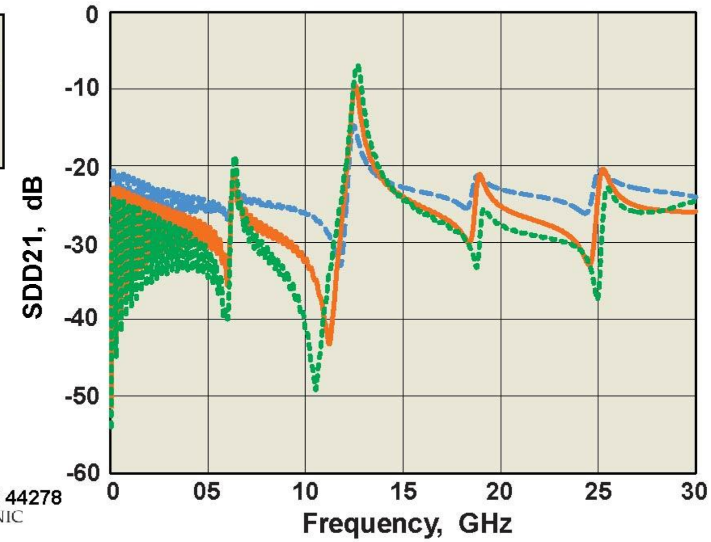


7 mils Wide Striplines



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





NOV_05 / 2013 / MJD / 44278
MAYO CLINIC SPPDG

SERPENTINE STRUCTURE STUDY SUMMARY

- 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

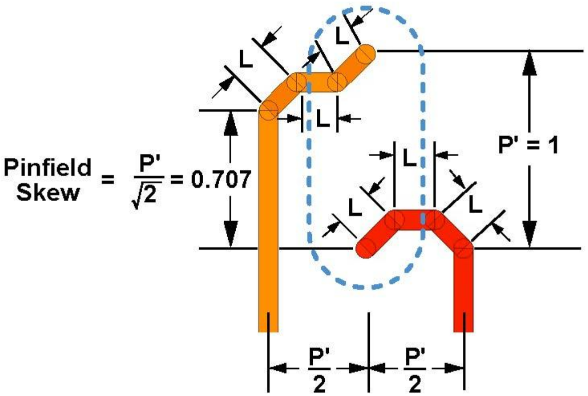
- Test board
  - Structure descriptions and measured results
  - Model comparisons to measurements
- Serpentine stripline structures
  - General periodic structure behavior
  - Serpentine structure descriptions
  - Electrical behavior of serpentine lines
- **Back-jogs for length tuning within differential pair**
  - Usage examples
- Summary

CORRECTING PIN-FIELD SKEW WITH BACK-JOGS

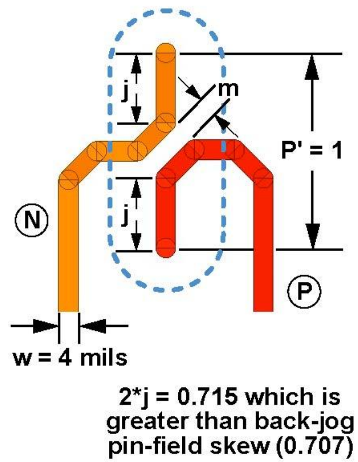
- We observe that a few stripline bends generally will not cause problems
- Use this result to try to reduce or eliminate jog-outs
  - Essentially route backward jog-outs, i.e., a back-jog to minimize pin-field skew
- Standard break-outs are 45 degree paths toward outside of pin-field to reach routing 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)

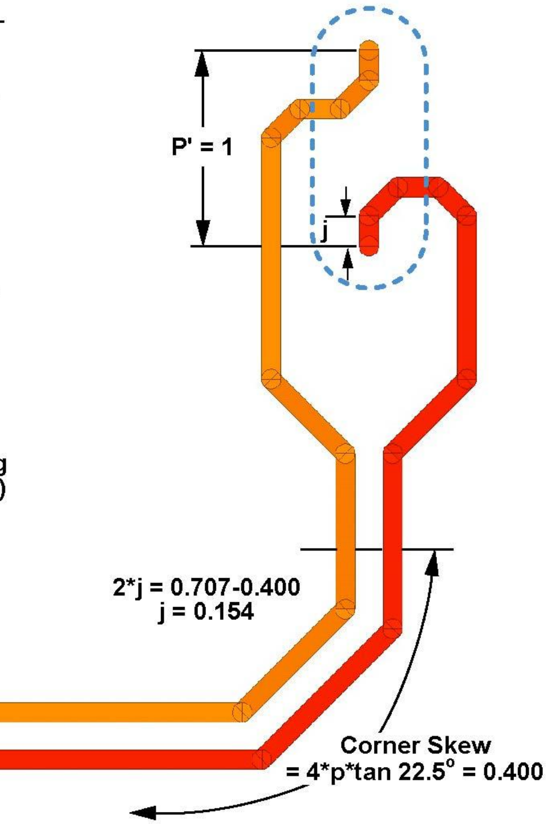
Maximum Pinfield Skew
(No Vertical Back-Jogs)



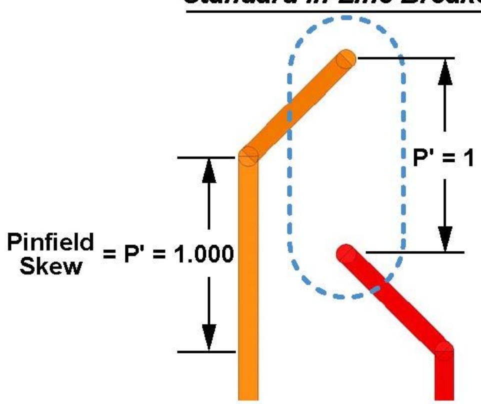
Maximum Tuning
(Allows Stripline Spacing (m) to be ≥ Stripline Width (w))



Pinfield Skew Set
To Zero Out Mitered Turn



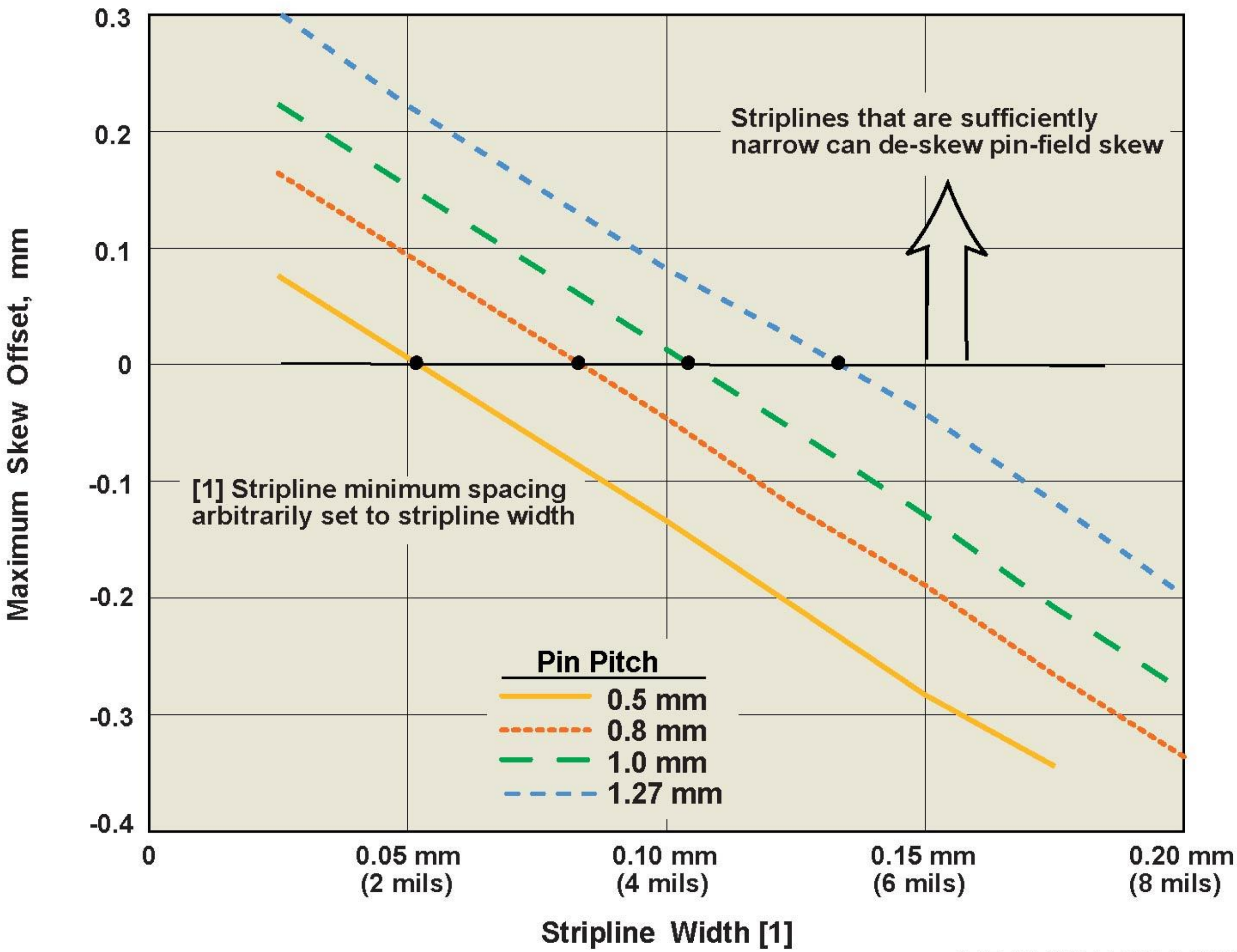
Standard In-Line Breakout



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

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)



OCT_22 / 2013 / MJD / 44257

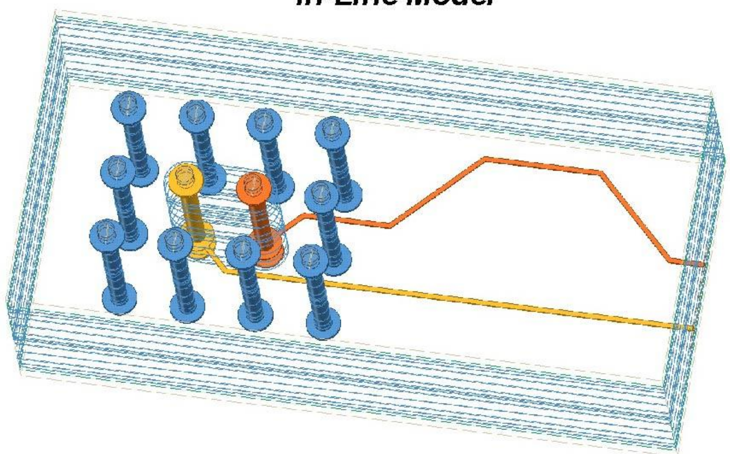
MAYO CLINIC SPPDG

BACK-JOG ELECTRICAL PERFORMANCE

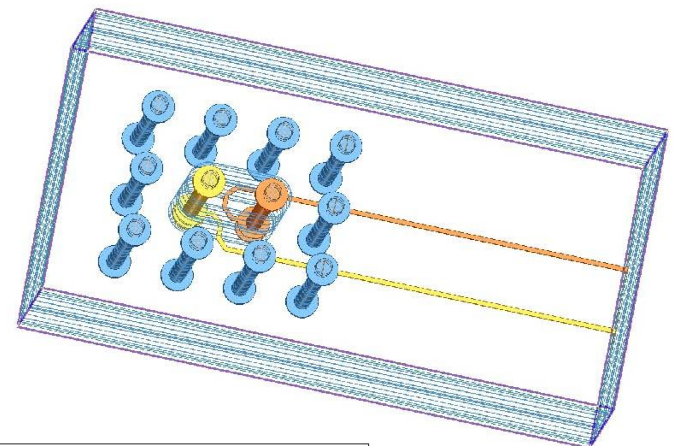
- We simulated a standard versus back-jog pin-field escape
  - Assumes 100 mil thick PCB and 10 mil diameter vias having 13 mil via stub, 26x65 mil oblong antipads
- Back-jog has somewhat higher return loss but lower frequency-dependant skew
  - Based on previous work, we believe that augmenting the 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

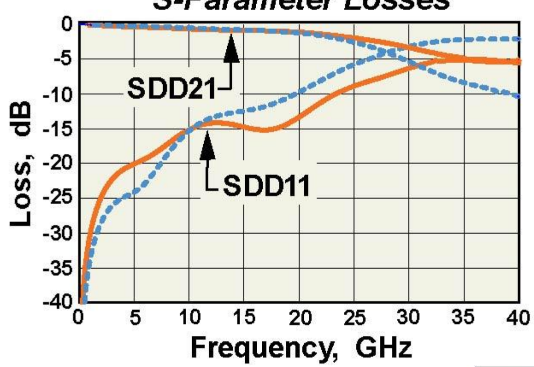


Back-Jog Model

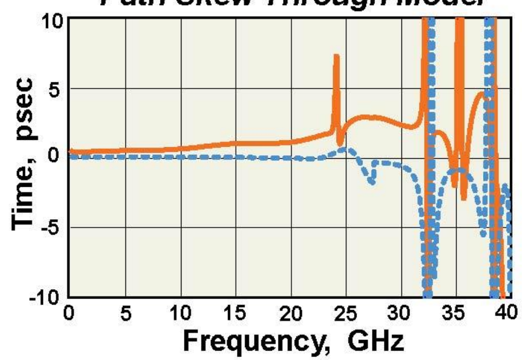


3 mil wide striplines, 1 mm pin pitch, 13 mil via stub, 100 mil board thickness

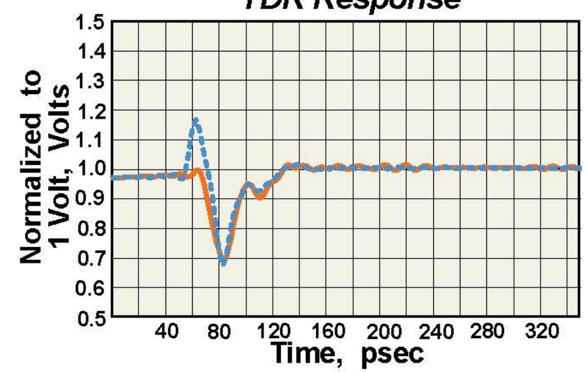
Differential S-Parameter Losses



Differential Path Skew Through Model



TDR Response



In-Line Model
Back-Jog Model

OCT_25 / 2013 / MJD / 44258
MAYO CLINIC SPPDG

OUTLINE

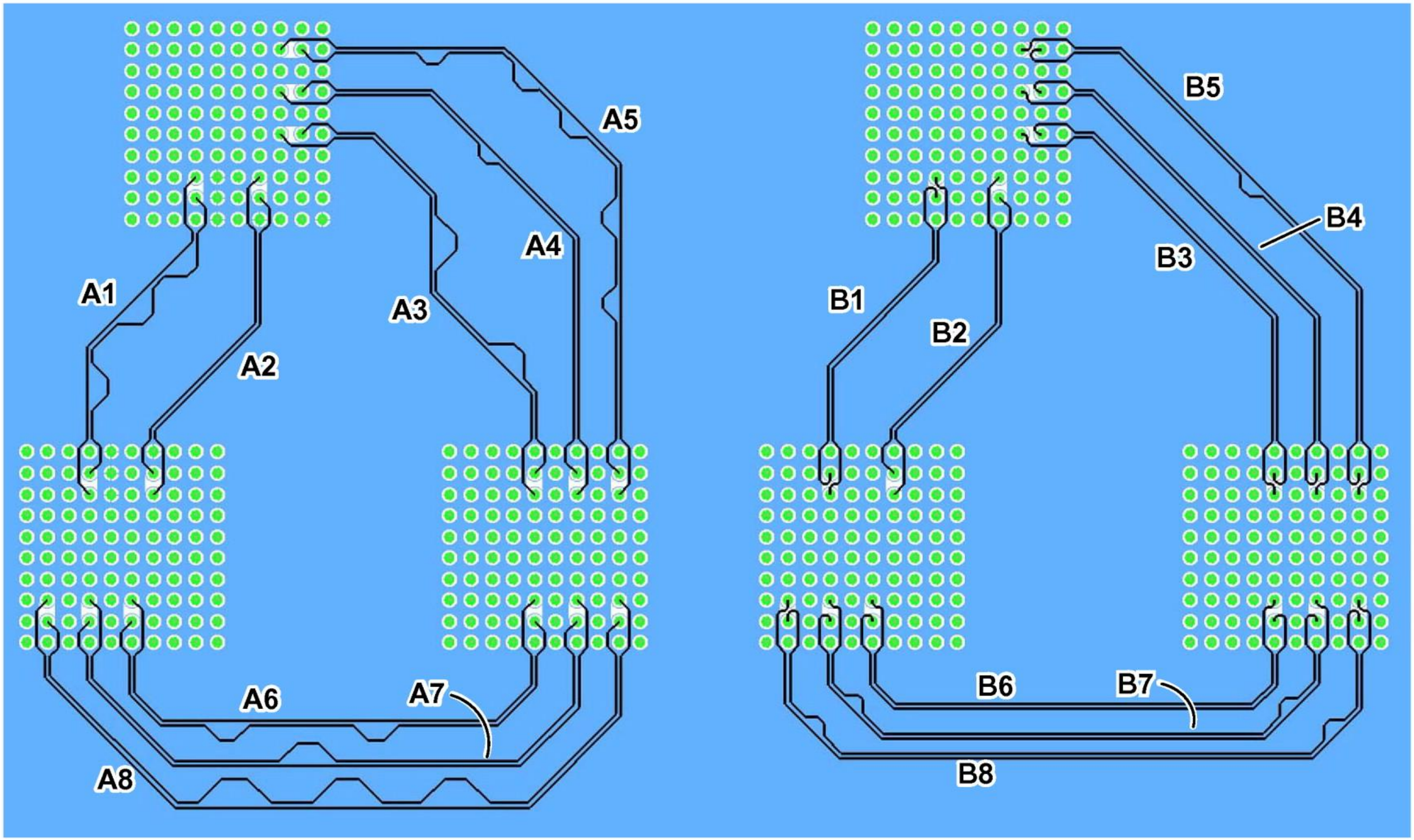
- Test board
  - Structure descriptions and measured results
  - Model comparisons to measurements
- Serpentine stripline structures
  - General periodic structure behavior
  - Serpentine structure descriptions
  - Electrical behavior of serpentine lines
- **Back-jogs for length tuning within differential pair**
  - **Usage examples**
- Summary

BACK-JOG USAGE EXAMPLES

- 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)



NOV_05 / 2013 / MJD / 44275

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