Broadband Slow Light in a Photonic Crystal Line Defect Waveguide

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Photonics BW e. V.

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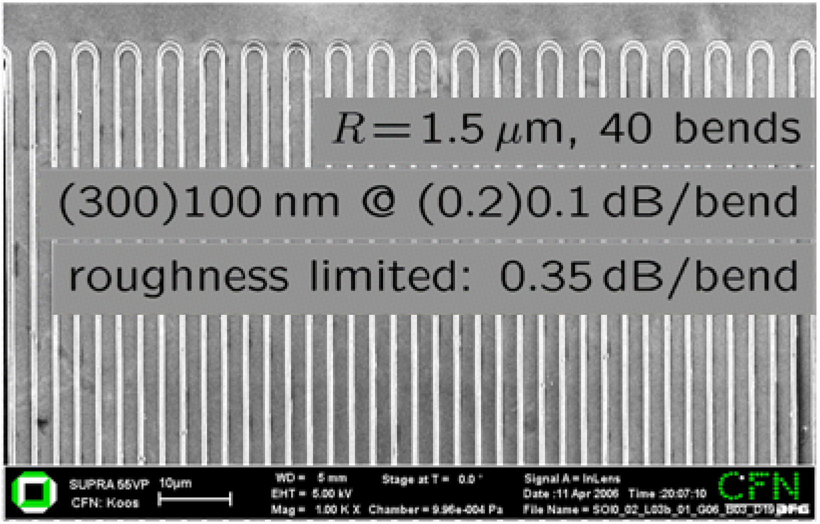
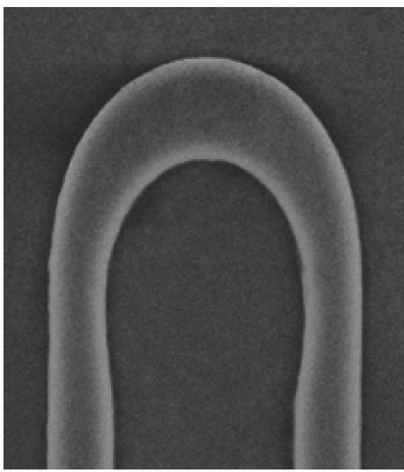
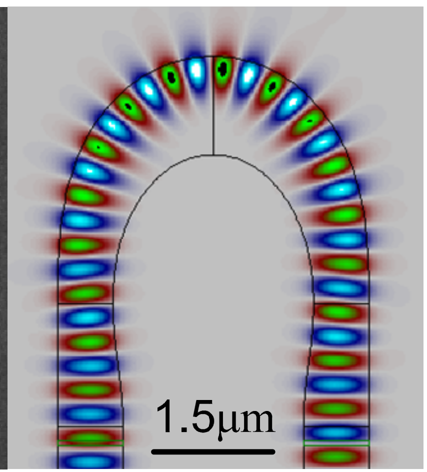
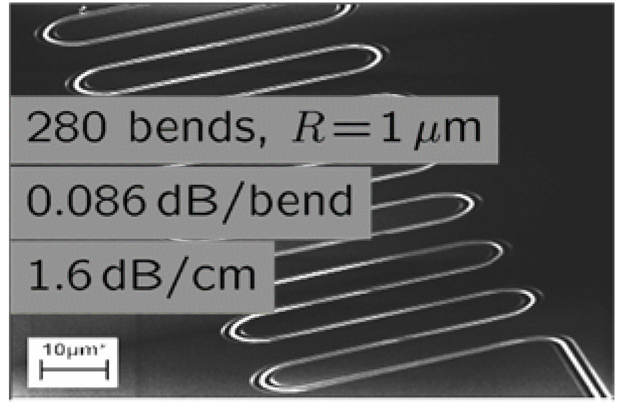
- Deutsche Telekom Stiftung.

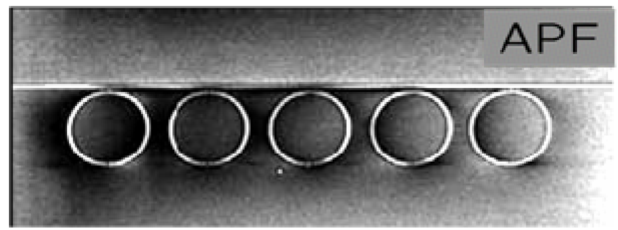
SOI Delay Lines with Bent Nanowires and Cascaded Resonators

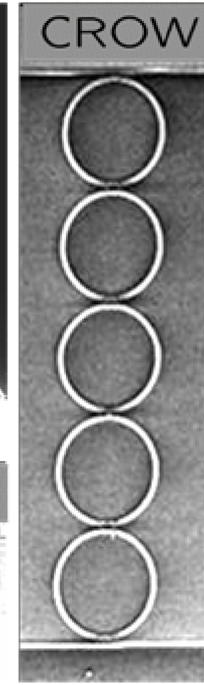












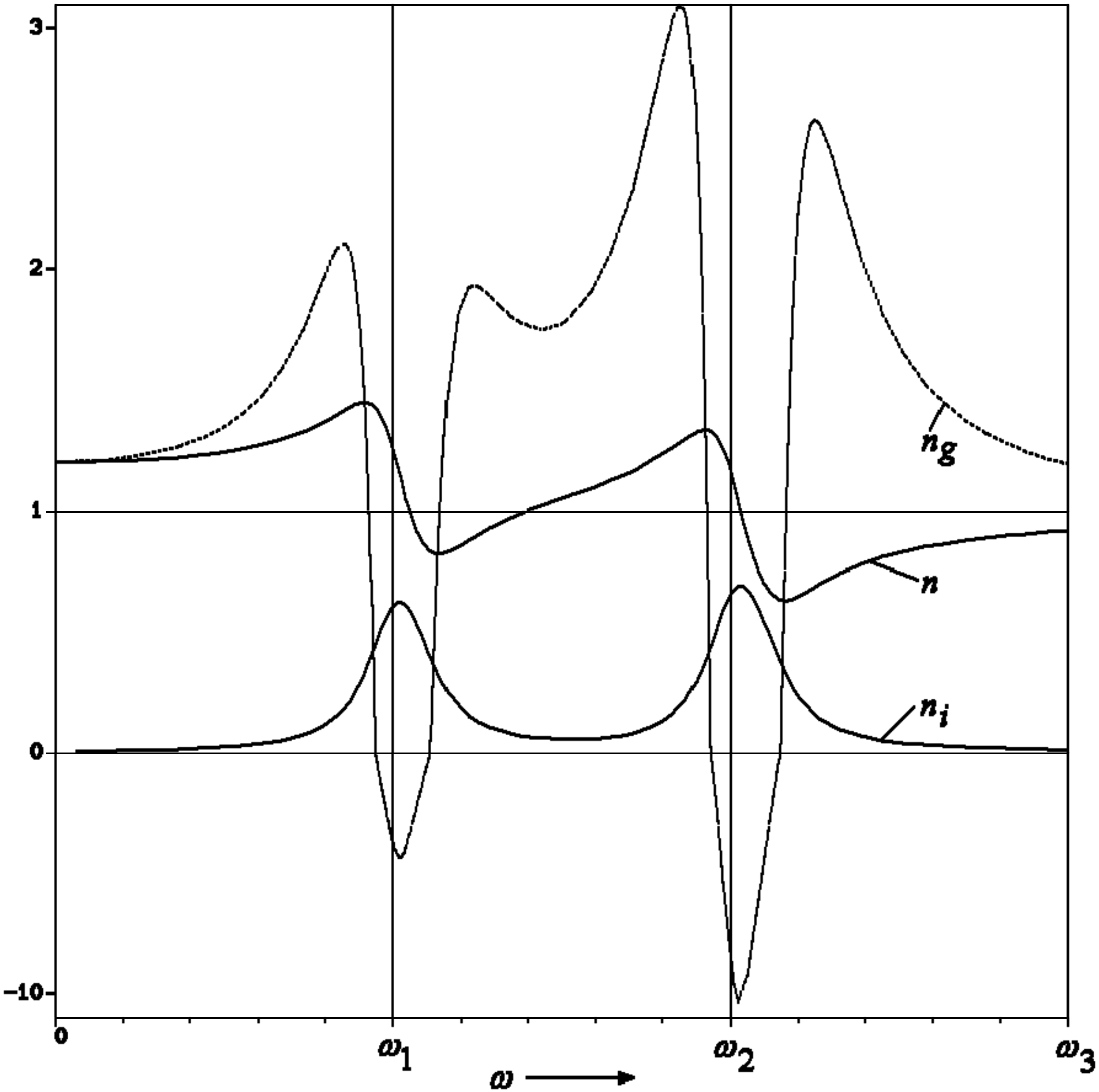
56 all-pass filt., $R=6.5\,\mu$m, $t_g=520$ ps, 1 Gbit/s, $600\times150\,\mu$m

100 coupled resonant opt. waveguides, $R=6.5\,\mu$m, $t_g=500$ ps, 5 Gbits/s, 10 bit @ 20 Gbits/s, $\mathrm{BER}=10^{-9}$

Koos, C.; Poulton, C.; Jacome, L.; Zimmermann, L.; Leuthold, J.; Freude, W.: Ideal trajectory for ultracompact low-loss waveguide bends. ECOC'06 Paper Tu1.4.6

Vlasov, Yu. A.; Xia, F.; Sekaric, L.; Dulkeith, E.; Assefa, S.; Green, W.; O'Boyle, M.; Hamann, H.; McNab, S. J.: Chip-scale all-optical group delay. OSA'06 Paper FThL1 (IBM Watson Res. Center)

Absorption, Refractive Index and Group Delay



$$E(t,z) \sim \mathrm{e}^{\mathrm{j}(\omega t - k_0 \overline{n}\, z)},$$

$$k_0 = \frac{\omega}{c},$$

$$\overline{n} = n - \mathrm{j}\, n_i,$$

$$n_g = n + \omega \frac{\mathrm{d}n}{\mathrm{d}\omega},$$

$$\frac{t_g}{L} = \frac{n_g}{c}$$

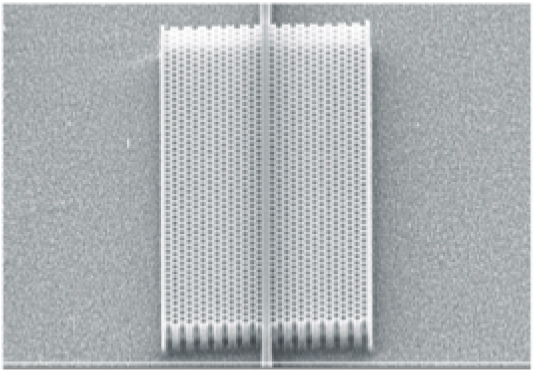
What is it good for to delay the light?

Potential of photonic crystals (PCs):

- By controlling dispersion, light might be slowed down
- High bandwidth as needed for components in fast communication systems

Applications of slow light in a PC:

- Optical modulators and nonlinear elements with reduced size and power
- Optical buffers and delay lines



Cooperation with Fraunhofer Heinrich Hertz Institute, Berlin

Basic component: Broadband slow light PC waveguide (WG)

- Optical pulse transmission at 4% of speed of light over 1.3 THz
- Effect of disorder on group velocity
- Verification with up-scaled microwave experiment

Outline

- Broadband slow light device
  - W0.75 photonic crystal waveguide
  - Coupling taper
- Verification with microwave experiment
  - Experimental pulse transmission setup
  - Pulse shape and group velocity measurement
  - Comparison to simulation
- Influence of disorder on group velocity
  - Measurement of 3 realizations
  - Numerical study of 19 realizations
- Summary

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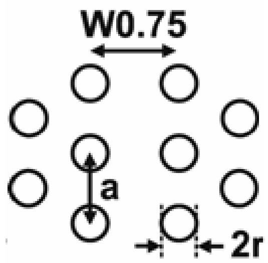
Broadband Slow Light Device

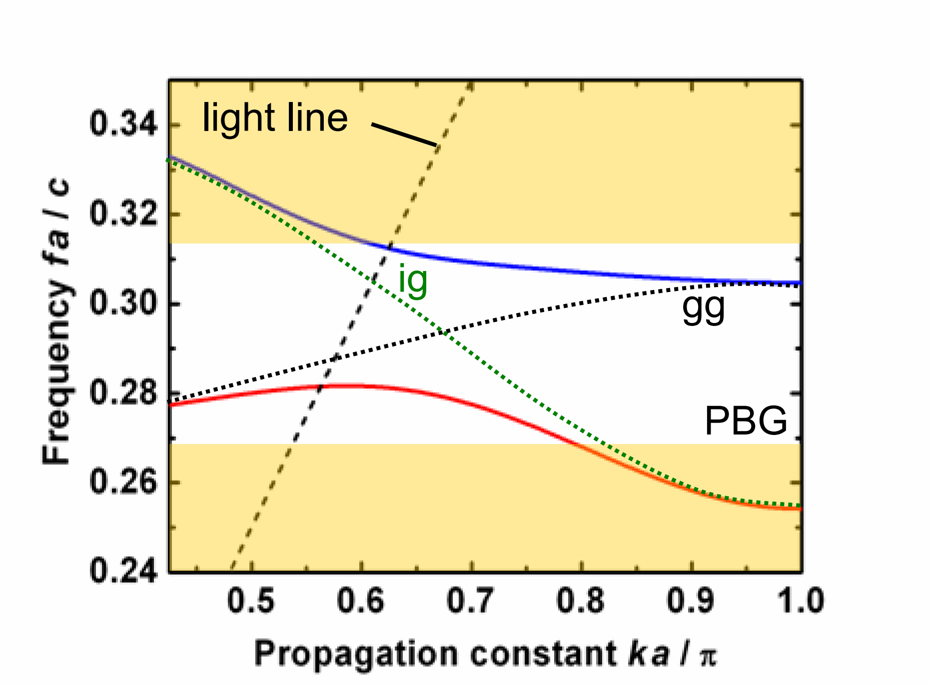
Design: High-index PC membrane (n = 3.16, h = 0.27 μm)

→ Broadband low group velocity of $v_g = 0.04 \times c$
for r / a = 0.25, W0.75 line defect, a = 0.45 μm



Anti-crossing of gap-guided and index-guided modes in PC-WG

A. Yu. Petrov and M. Eich, Appl. Phys. Lett. 85, 4866 (2004)



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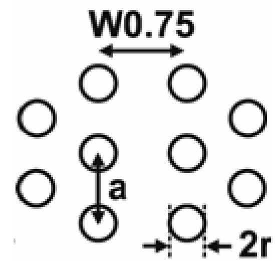

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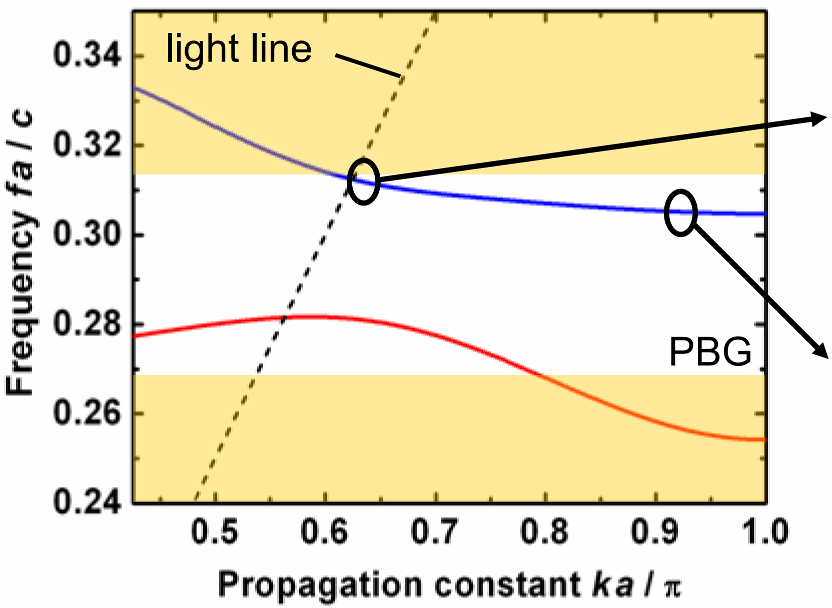
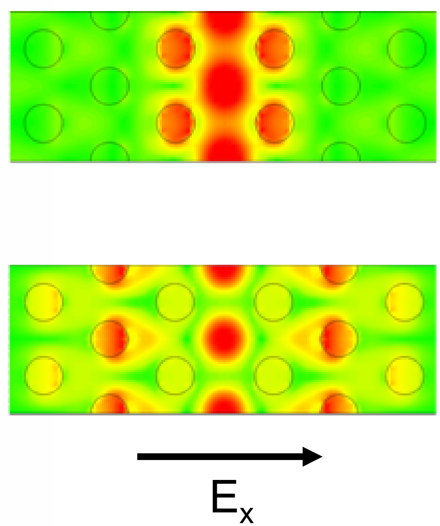
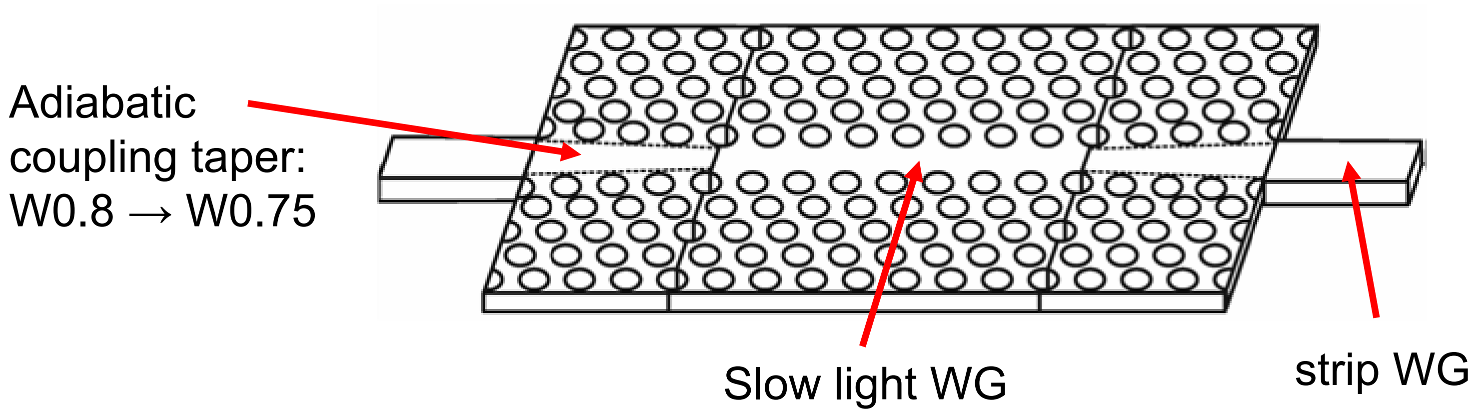


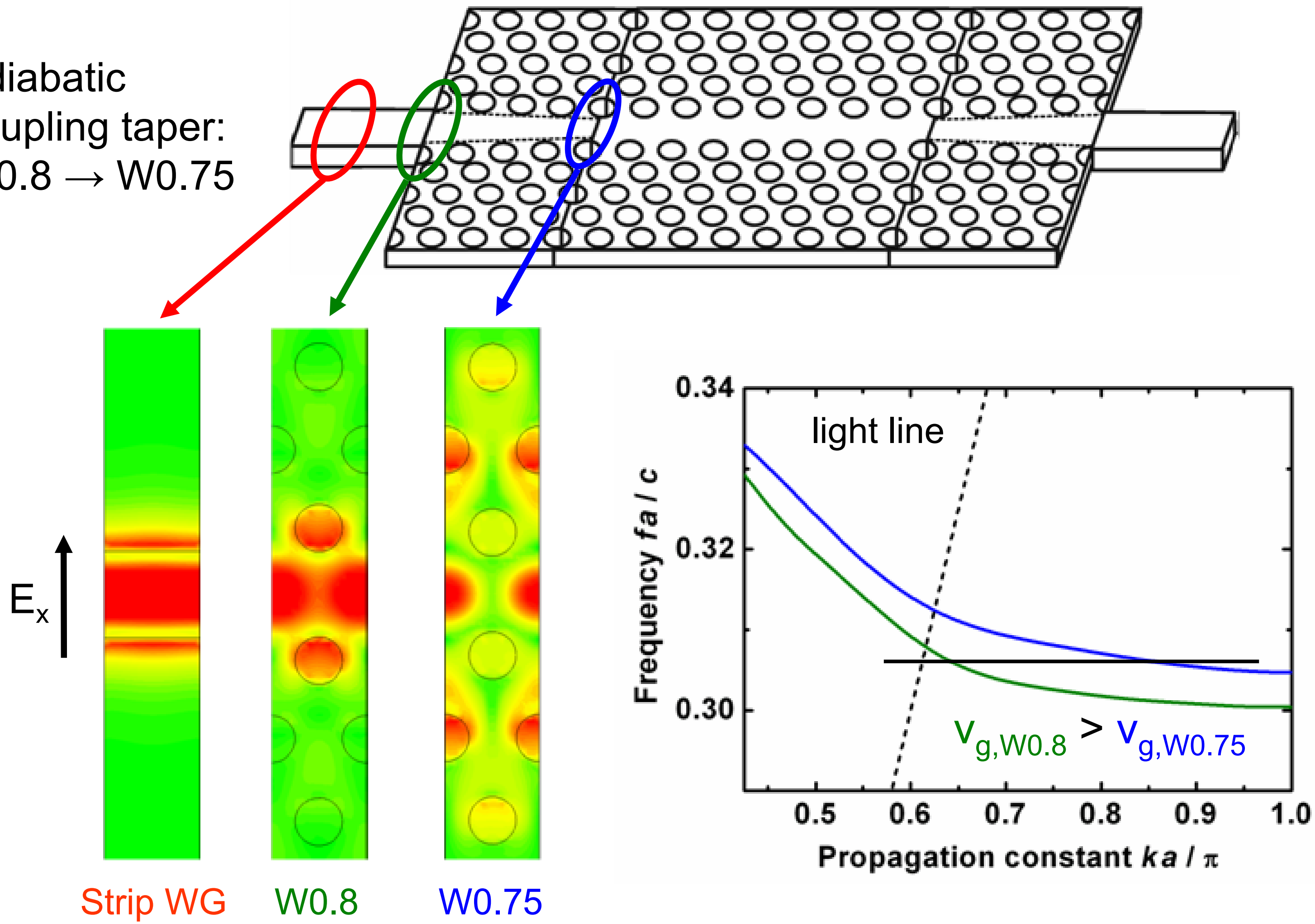


Coupling Taper



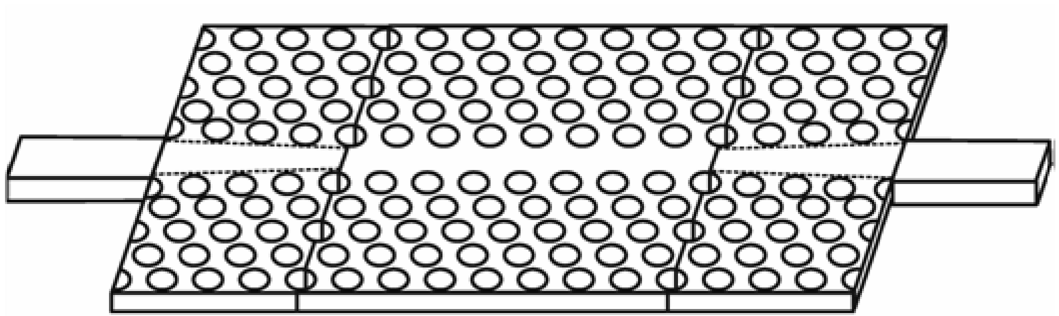
Coupling Taper

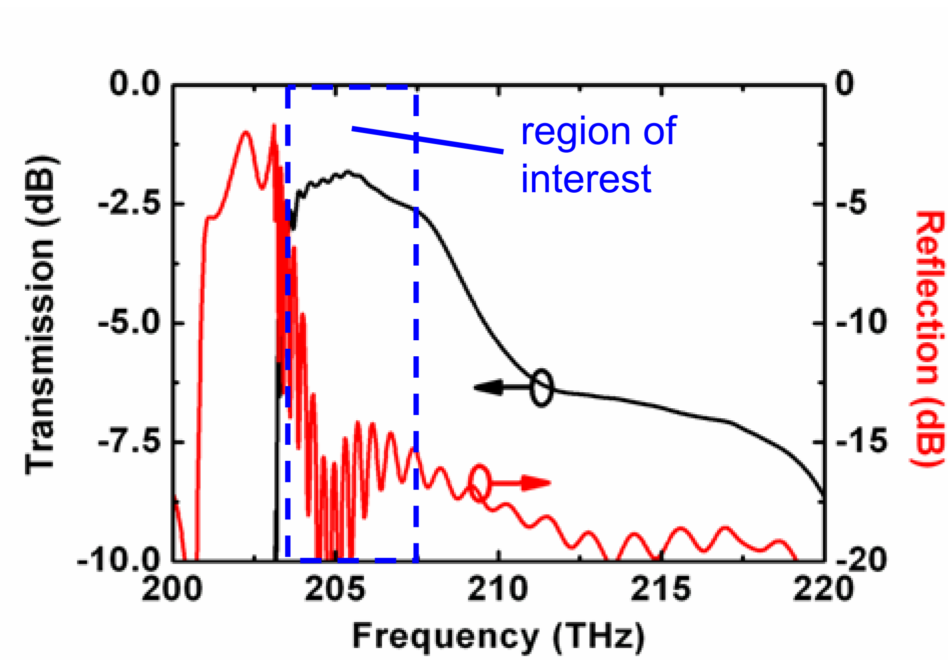
Adiabatic coupling taper:
W0.8 → W0.75



Overall Transmission and Reflection

Adiabatic
coupling taper:
W0.8 → W0.75





Coupling strip WG to W0.75:

Losses better than 1.25 dB per interface

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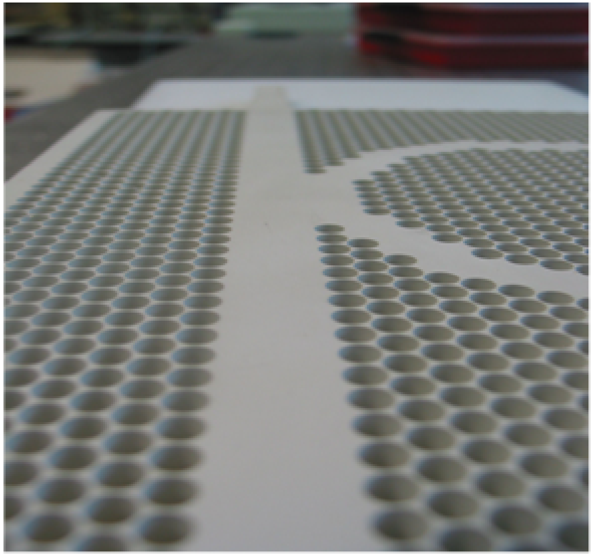
Verification with Microwave Experiment

Upscaled structure dimensions by 20,000 (0.4 µm → 8 mm)
Downscaled operating frequency by 20,000 (200 THz → 10 GHz)

Advantages:

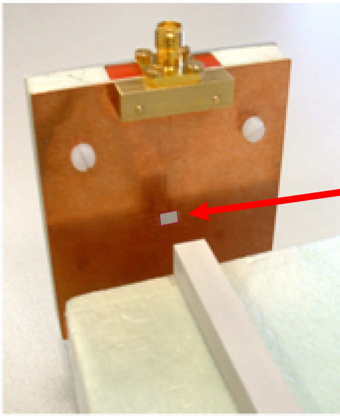
- Very accurate fabrication
  Equivalent accuracy of 0.5 nm
  Allows to study disorder
- Very accurate measurement equipment
- Flexible and modular setup



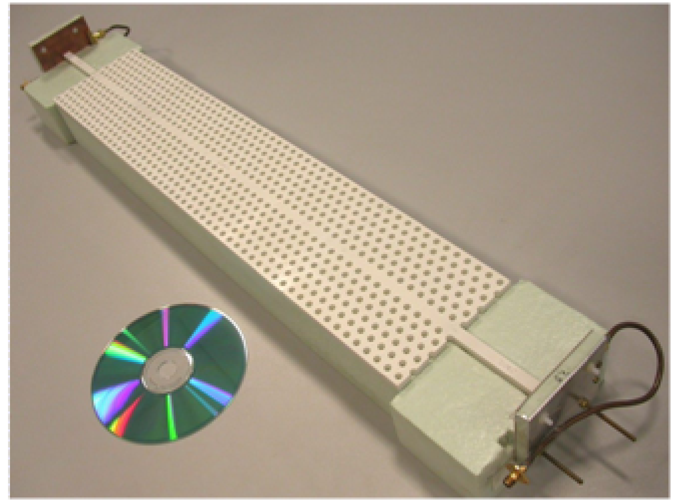
Material:

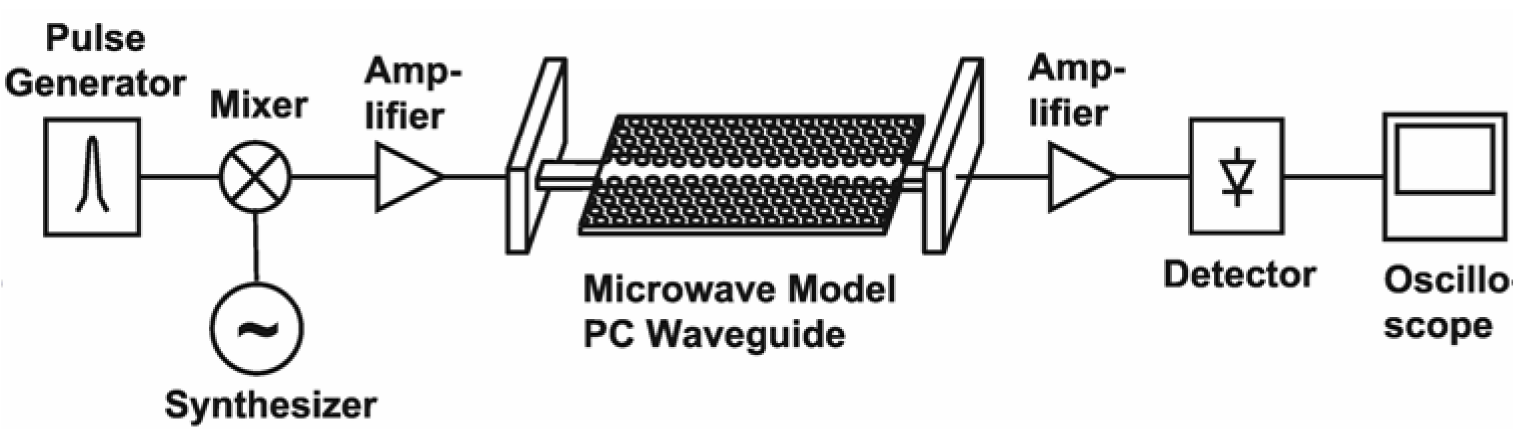
Ceramic-filled PTFE, *n* = 3.16 @ 10 GHz

Experimental Setup



Slot antenna to excite waveguide mode near 10 GHz





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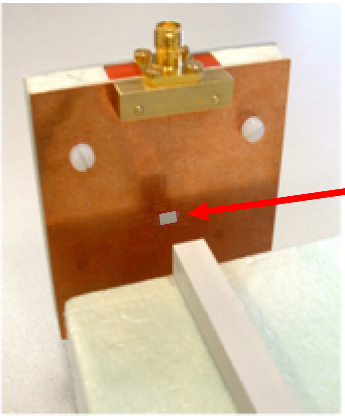

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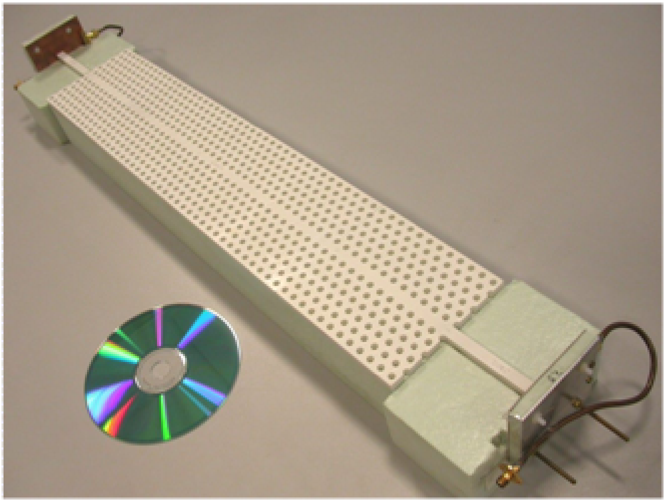
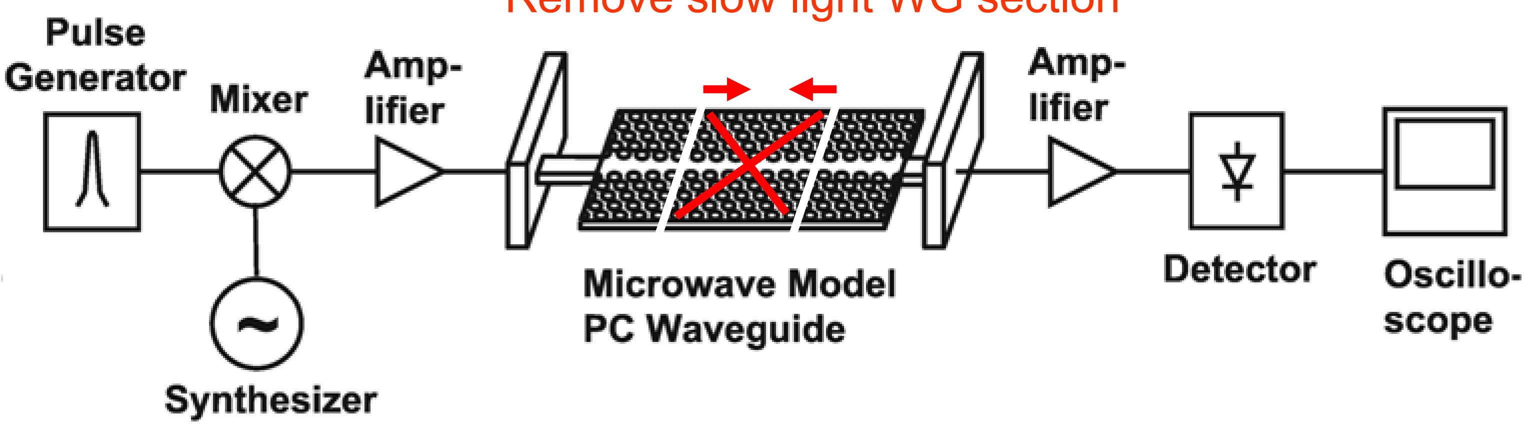
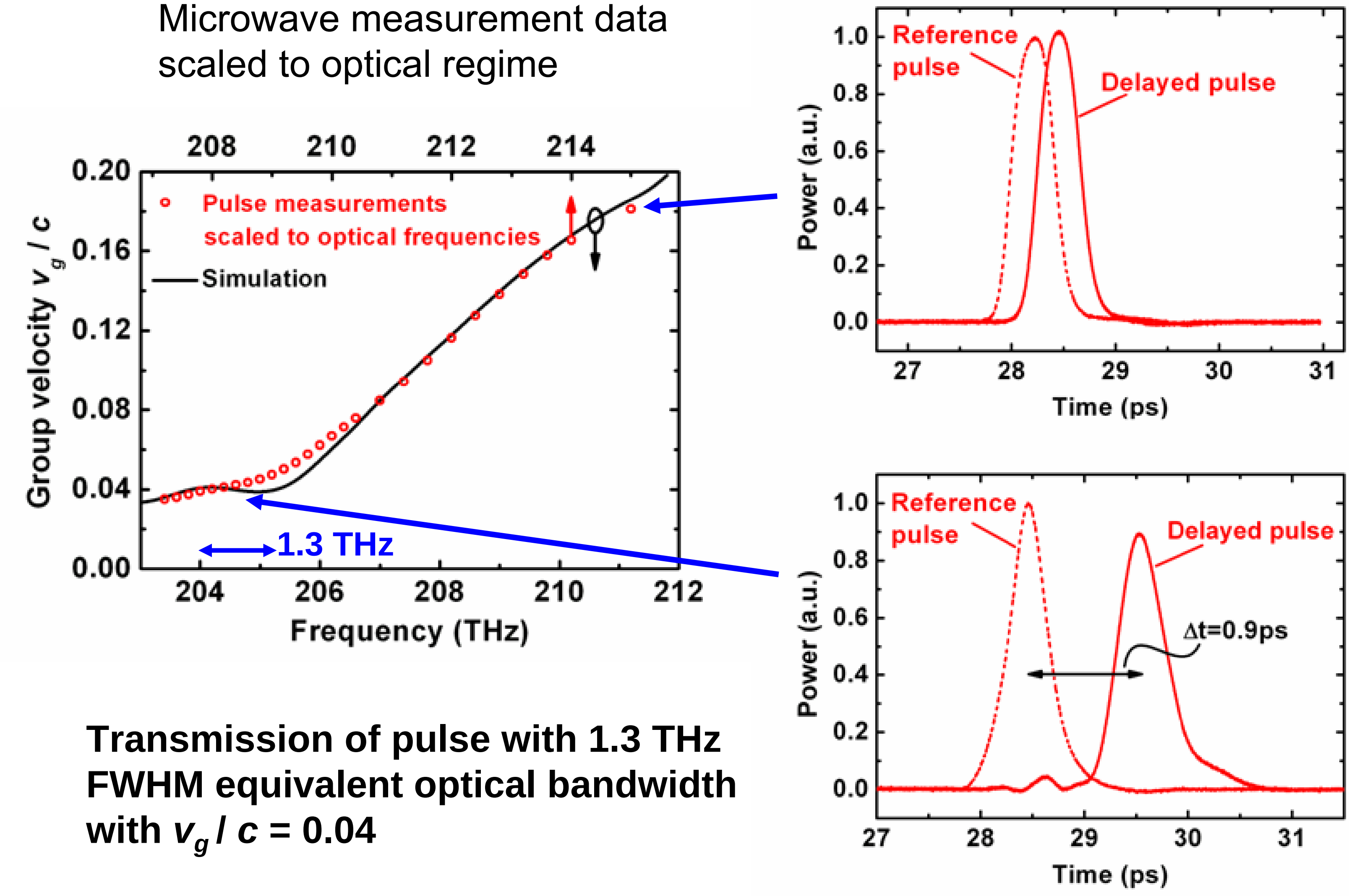


Reference measurement:
Remove slow light WG section



Pulse Shape and Group Velocity Measurement

Microwave measurement data
scaled to optical regime



Transmission of pulse with 1.3 THz FWHM equivalent optical bandwidth with v_g / c = 0.04

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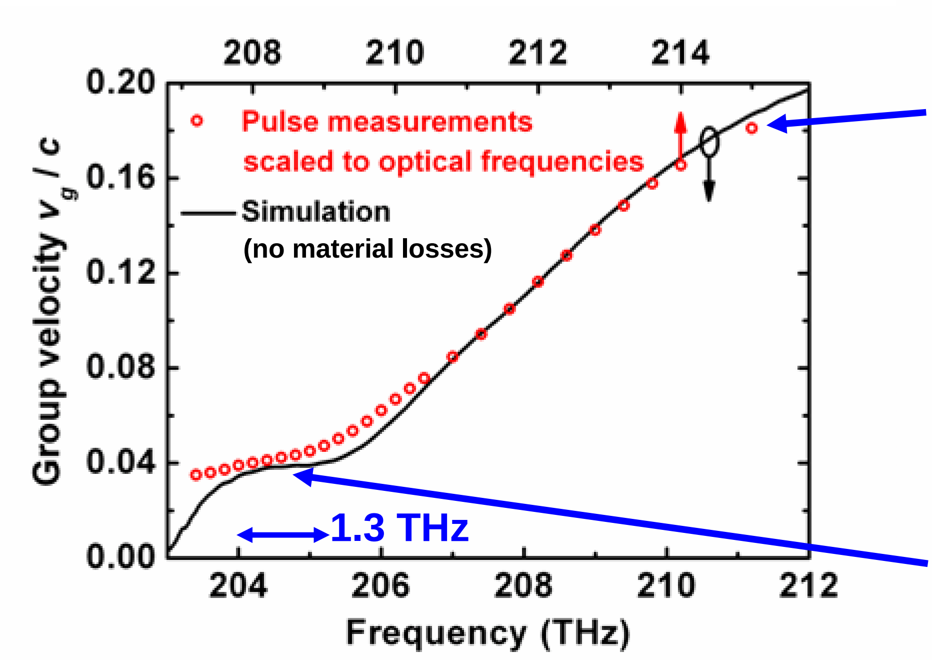
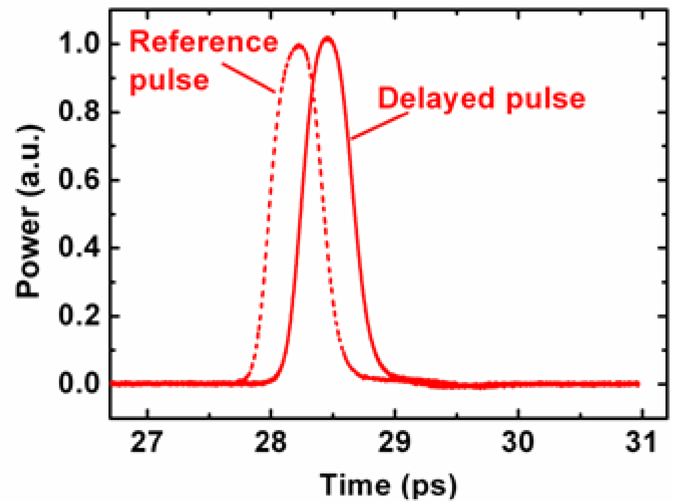
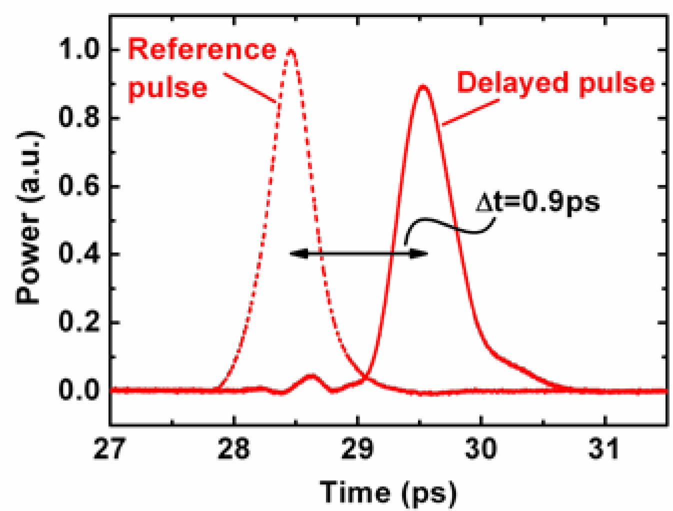






Transmission of pulse with 1.3 THz FWHM equivalent optical bandwidth with v_g / c = 0.04

Applications

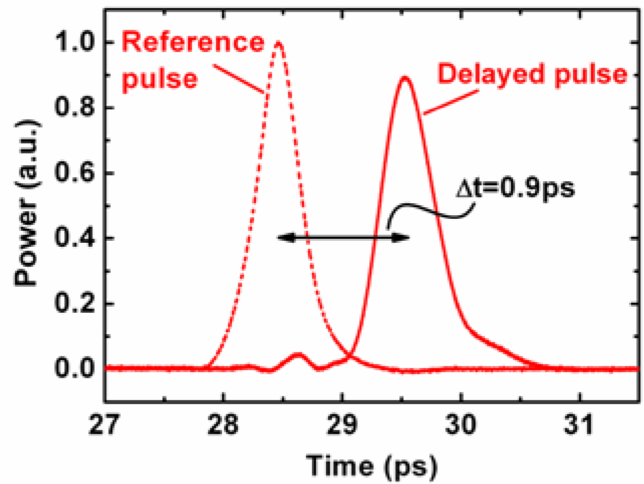
Delay line

$$C_{\text{Delay-Bandwidth}} = T_{\text{Storage}} \times B_{\text{Packet}}$$ Number of stored bits

Criteria for PC length: Temporal pulse spreading by chromatic dispersion

Measured pulse:
1.3 THz FWHM $\rightarrow C_{\text{Delay-Bandwidth}} \approx 1$

Possible:
125 GHz FWHM $\rightarrow C_{\text{Delay-Bandwidth}} \approx 120$



Modulator

Infiltration of PC-WG with electro-optic polymer
Potentially very fast (> 10 GHz) and small (< 1 mm)

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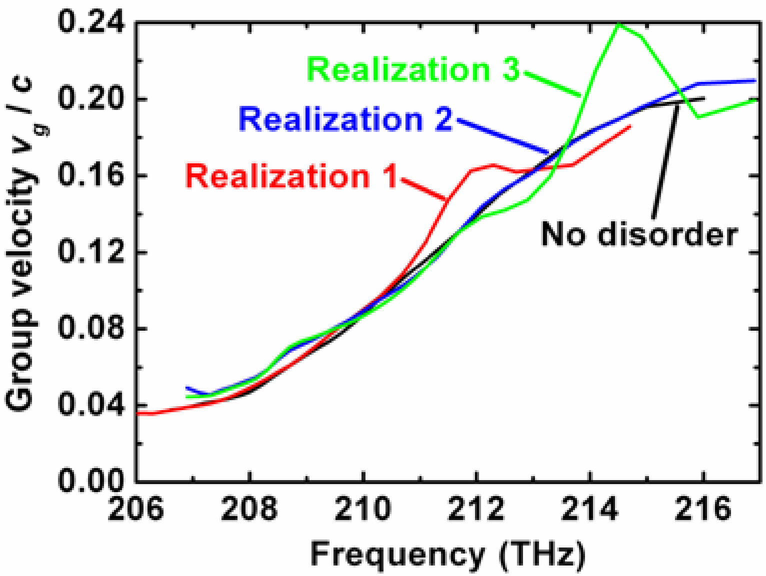
Influence of Radial Disorder

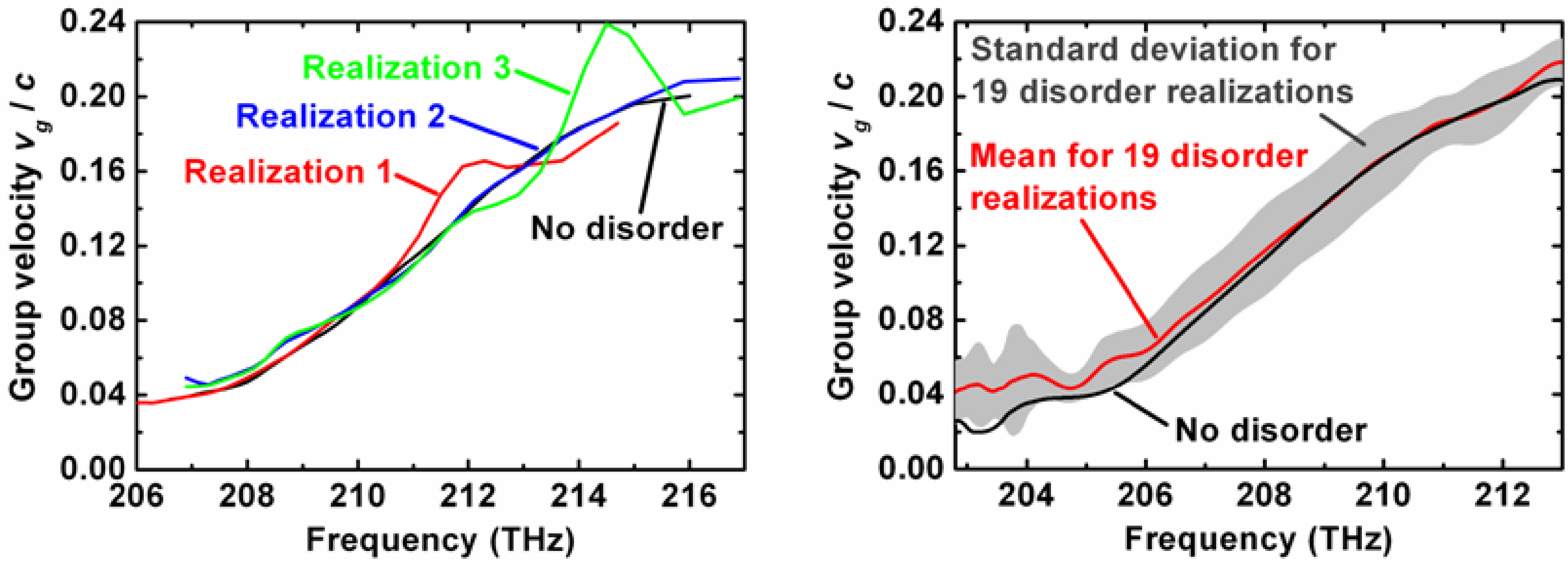
Microwave Measurements:
15 Periods of PC-WG, 5%
normally distributed radial disorder



Influence of Radial Disorder

Microwave Measurements:
15 Periods of PC-WG, 5% normally distributed radial disorder

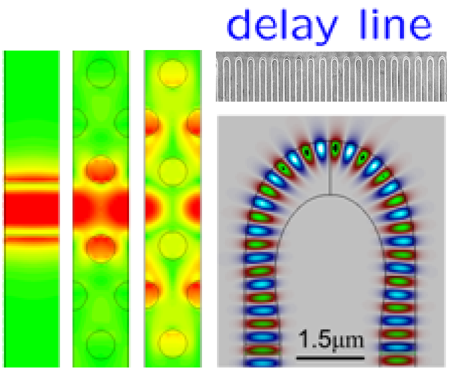
Simulations with Finite Integration Technique:
Lossless materials



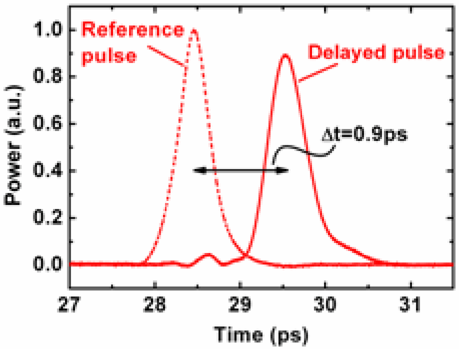
Ensemble average of group velocity increased near v_g / c = 0.04, but performance of component is not significantly impaired.

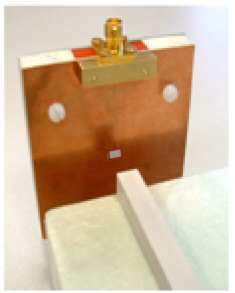
Summary

- Broadband slow light device
  - Low v_g in PC-WG away from band edge
  - Efficient Coupling Taper



- Microwave pulse transmitted
  - $v_g / c = 0.04$ for 1.3 THz equivalent optical pulse bandwidth
  - Good agreement with simulations





- Influence of radial disorder
  - Ensemble average of v_g increased near $v_g / c = 0.04$, but:
  - Component still performing well