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Workshop on Coherent Phenomena in Disordered Optical Systems

26 - 30 May 2014

Slow-light Propagation in Photonic Nano-Structures

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OUTLINE

- **Motivations & Background**
- **Slow-light in photonic nano-structures**
- **Summary**

Why slow light?

Motivations

Applications that beyond the human's curiosity:

- Compact light delay line, Optical buffer;
- Beams forming, regeneration;
- Retiming, Synchronization, (De)MUX, Correlator;
- Compact optical switch, modulator;
- Enhancement of optical nonlinearities.

Conclusion:

Mostly in communications & optical data processing.

Methods for slow light

Material dispersion

- Electromagnetically Induced Transparency in atomic media
- Coherent Population Oscillations in semiconductors
- Nonlinear gain and loss characteristics in fibres

Structural dispersion using Photonic structures

- Ring Resonators
- Periodic Structures(Photonic crystals)
- Chirping Structures

Conclusion:

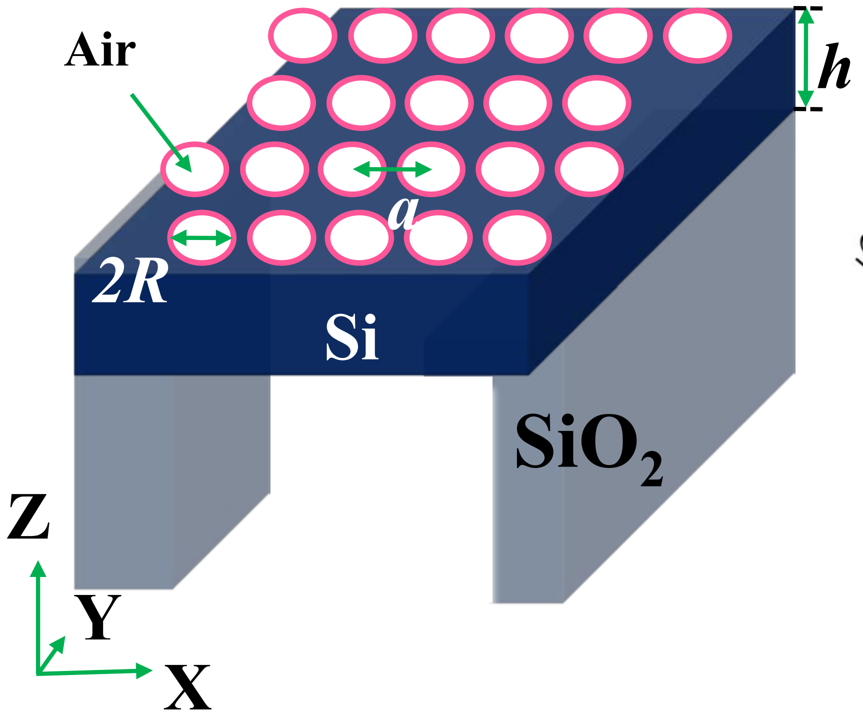
Slow light in structural dispersion would be more practical to be applied in integrated optical systems in the near future.

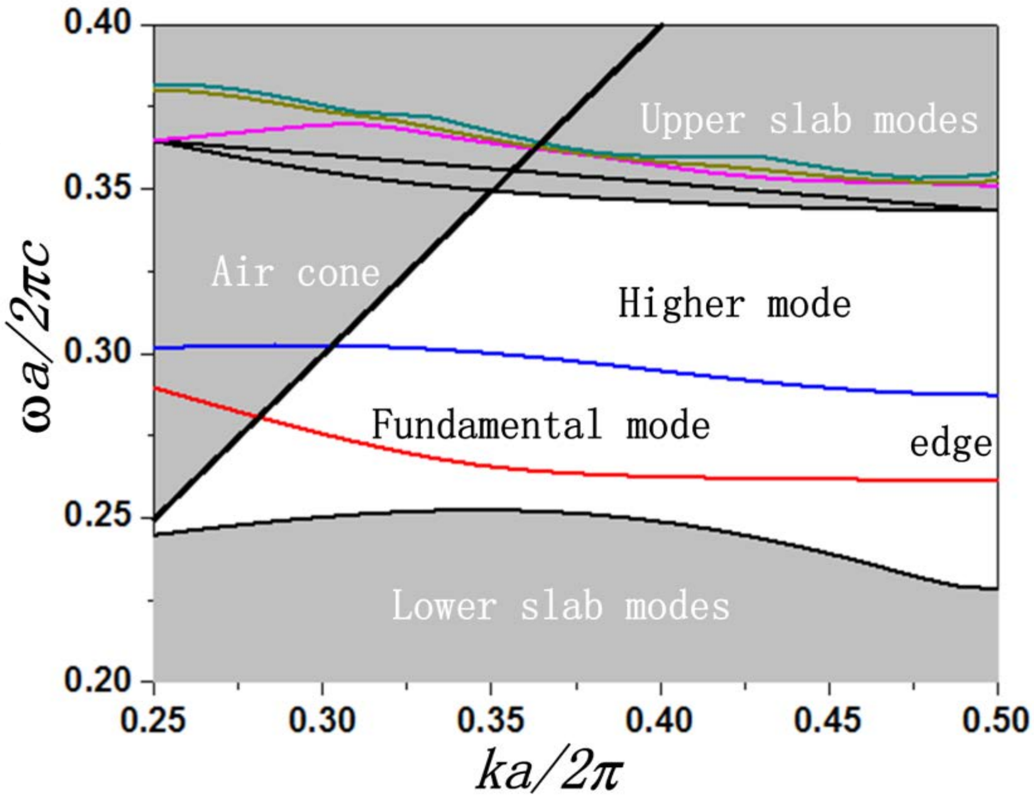
Slow-light in photonic nano-structures

- Principles of SL in photonic structures
- Slow light in 2D structures
- Slow light in 1D structures

Principles of slow light in periodic waveguides

The group velocity of light: $V_g = d\omega/dk$

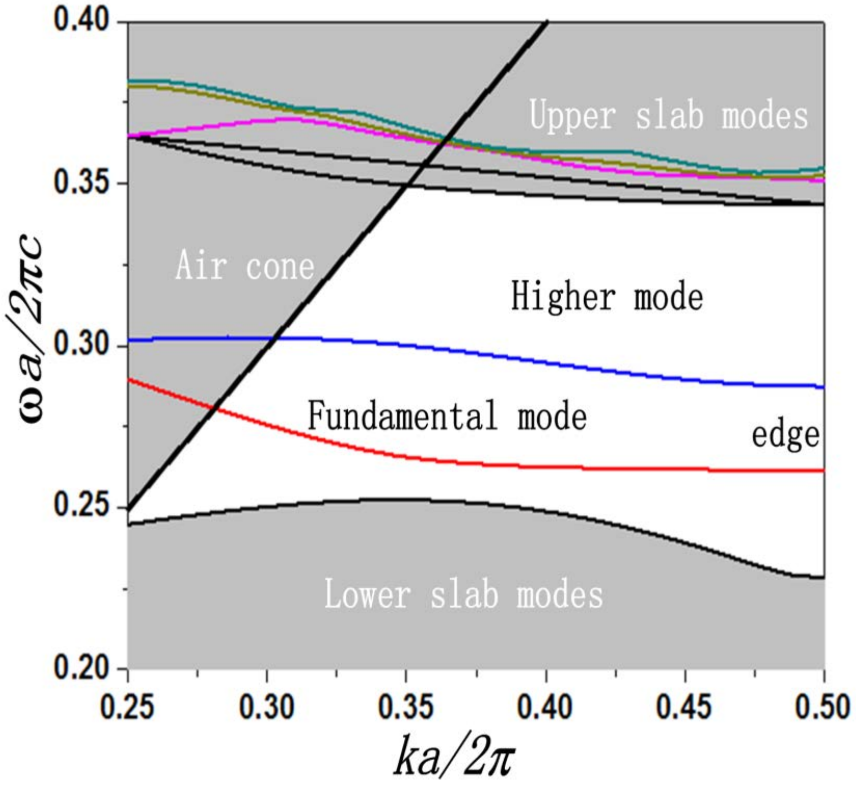




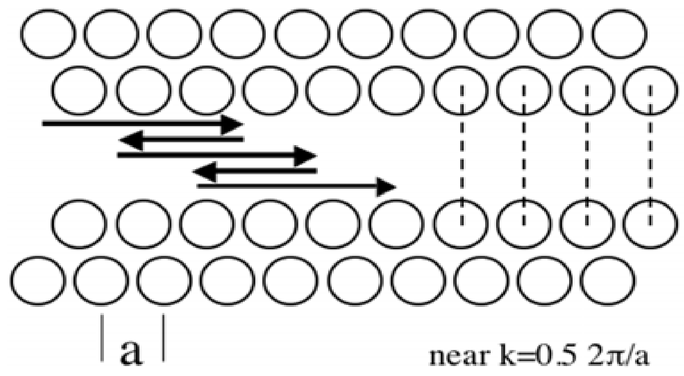
Band structure of a silicon PC Slab

Two possible mechanisms for slow light

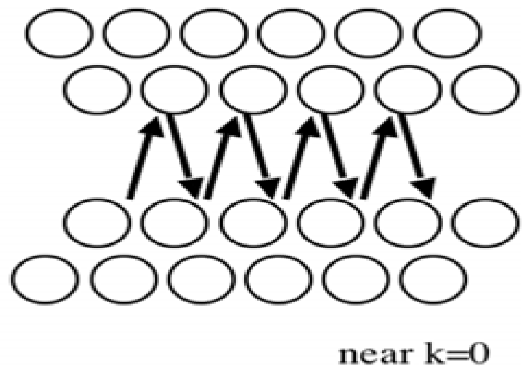
The group velocity of light: $V_g = d\omega/dk$



Band structure of a silicon PC Slab



Coherent backscattering.



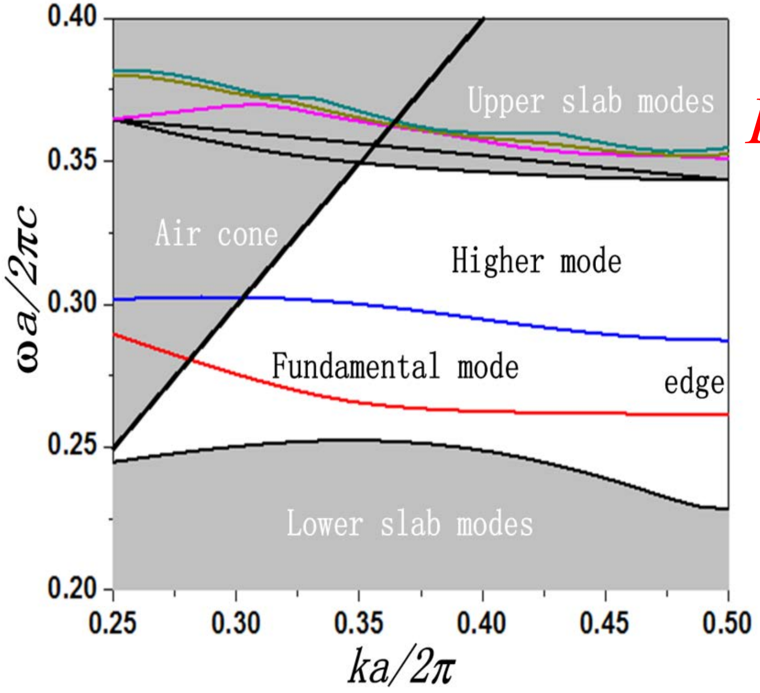
Omni-directional reflection.

T. F. Krauss. J Phys D Appl Phys 40, 2666-2670 (2007).

Dispersion issue in slow light waveguides

The group velocity dispersion, which will cause the propagation of signal distortion.

$$\beta_2 = d^2k/d\omega^2$$
$$= 1/c\ (dn_g/d\omega)$$



Band structure of the PC

Delay Bandwidth limit of slow light:

$$n_g = c/v_g$$
$$= cdk/d\omega$$
$$= d(n\omega)/d\omega$$
$$= n + \omega dn/d\omega$$

When $n_g >> n$,

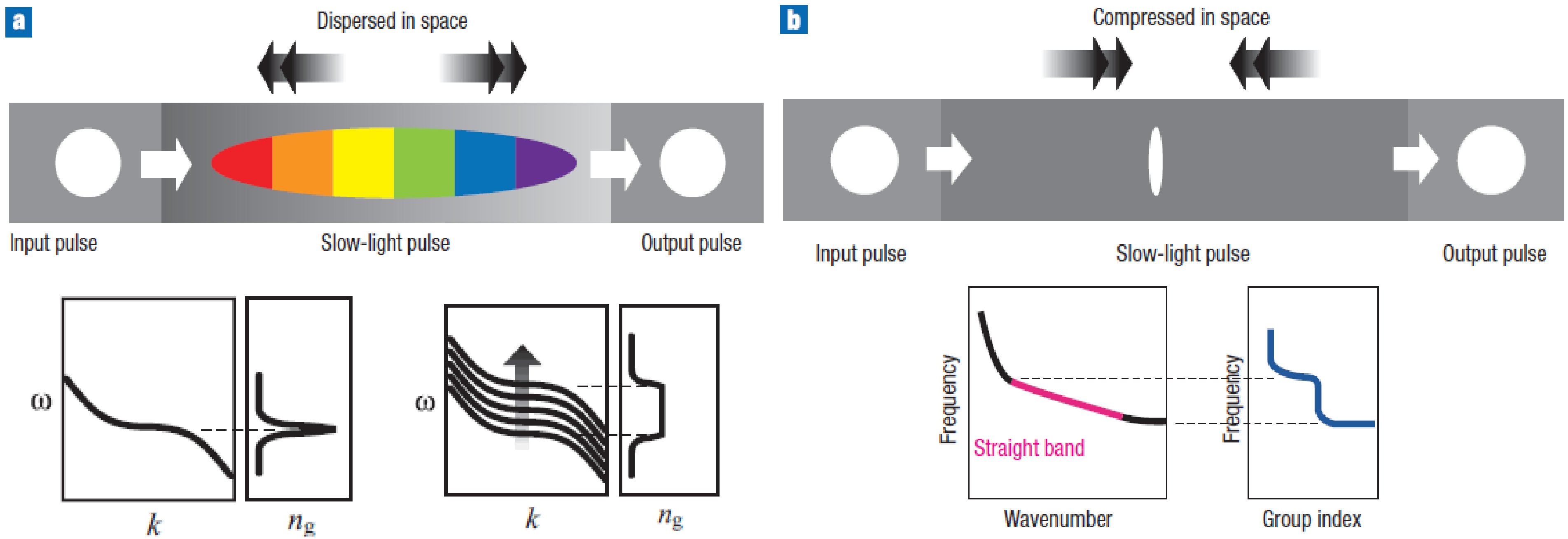
$$n_g \approx \omega dn/d\omega$$

$$\boldsymbol{n_g\, d\omega/\omega \approx dn}$$

$$\boldsymbol{dn_{Max} < \triangle k/\omega}$$
$$\boldsymbol{= (0.5-0.25)/0.25}$$
$$\boldsymbol{= 1}$$

T. Baba, et.al, J Phys D Appl Phys 40, 2659-2665 (2007).

Schematics of low dispersion slow light

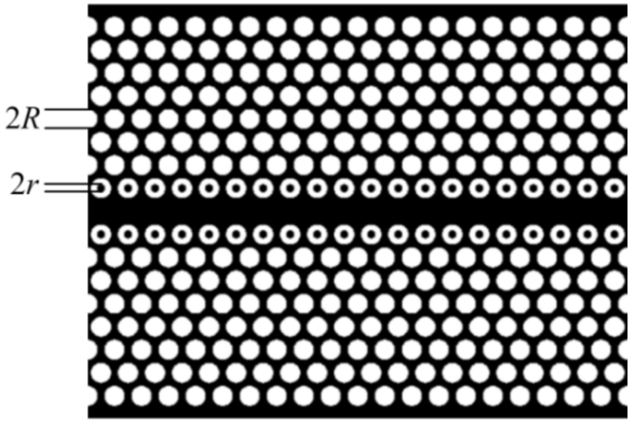


(a) Dispersion-compensated slow-light device with chirped structure.

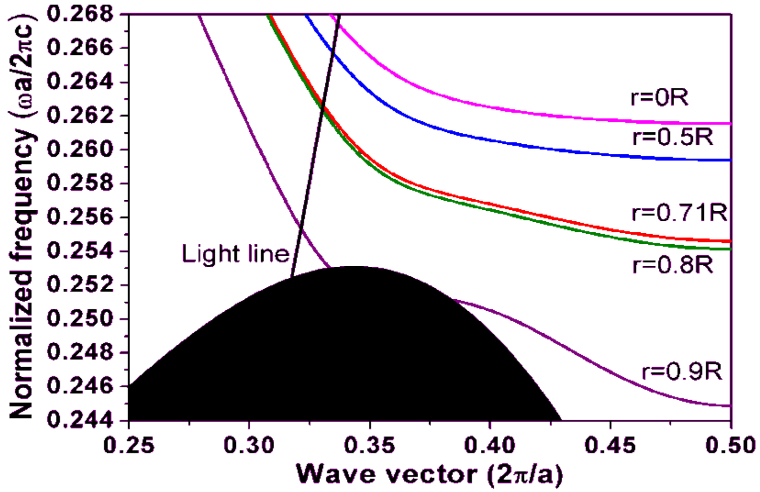
(b) Zero-dispersion slow-light device.

T. Baba, Nature Photonics 2, 465-473 (2008).

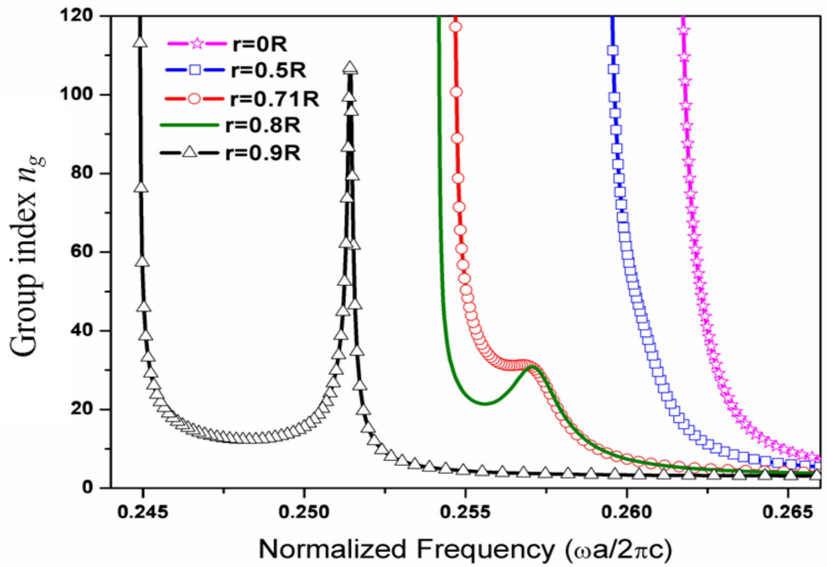
Slow light in 2D periodic structures



Schematic structure of line defect PC waveguide, black denotes silicon and white denotes air.

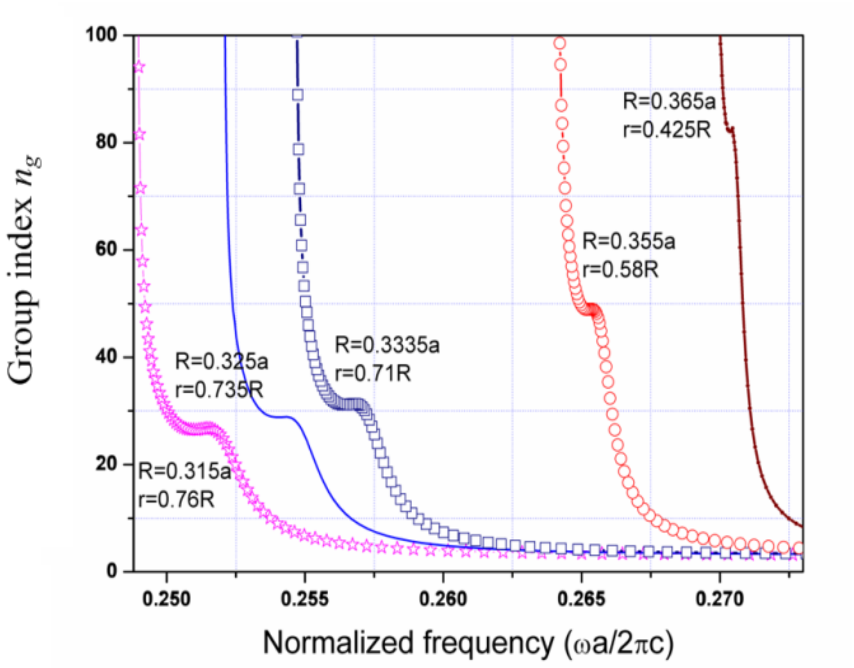


Photonic band of the main propagation mode for R=0.3335a, and r is taken as a parameter.

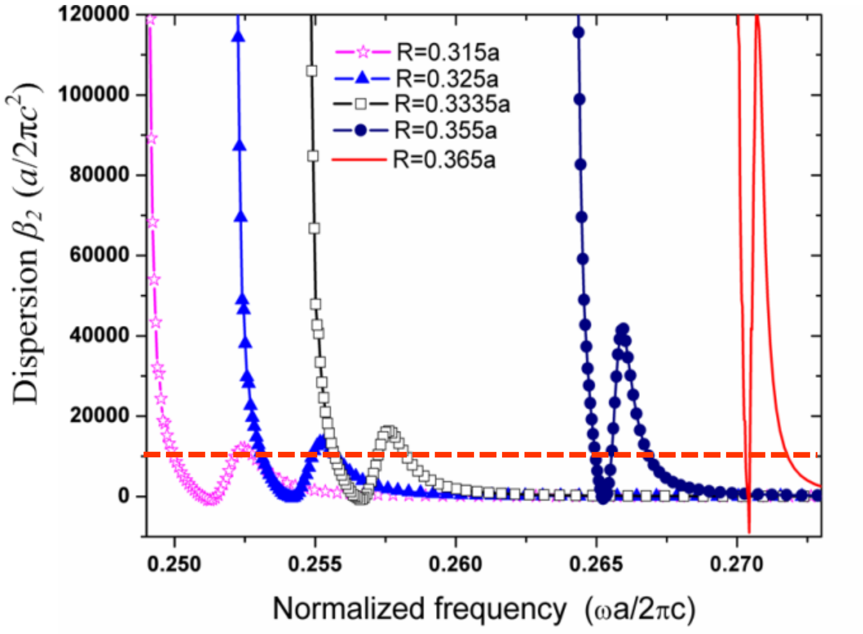


Group index n_g characteristics of PC waveguide, R is fixed to 0.3335a and r is varied corresponding to the band structure.

Group index characteristics



Optimized Group index characteristics, R is varied and r is optimized to obtain the low GVD characteristics.



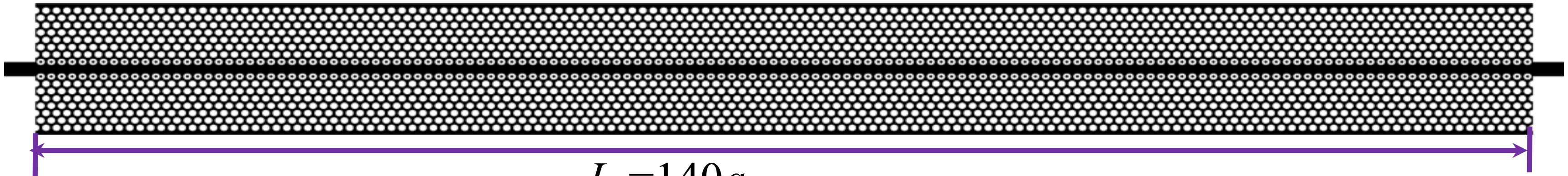
The corresponding group velocity dispersion characteristics.

If $\beta_2 < 10000$ $(a/2\pi c^2)$, about 7.42 ps^2/mm for 1550nm.

At n_g=82 with $\Delta\omega/\omega$=0.06% for R=0.365a, it means a 0.93nm bandwidth;

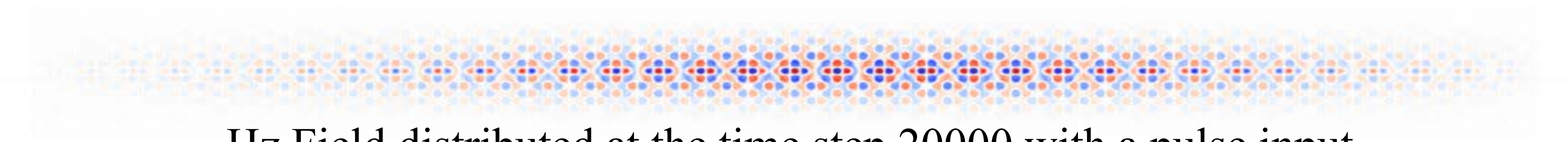
At n_g=26 with $\Delta\omega/\omega$=0.896%, about 13.89nm bandwidth for R=0.315a.

FDTD simulation of the waveguide

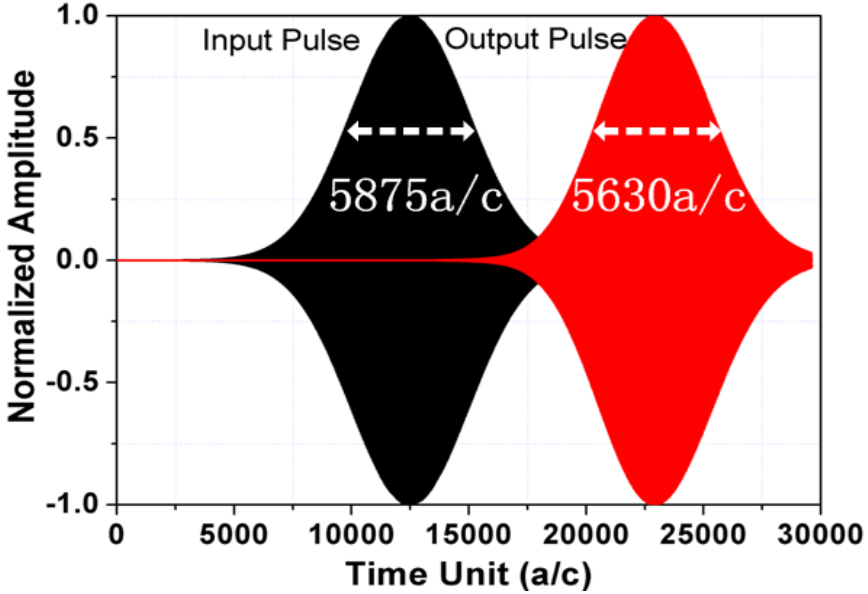


L_d=140*a*

Structure of the symmetric line defect PC waveguide simulated.

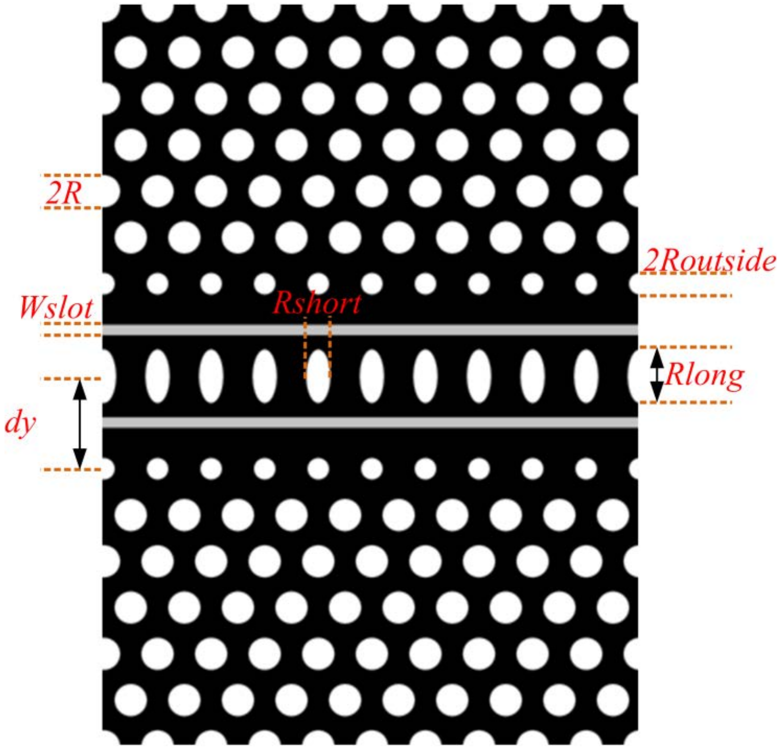


Hz Field distributed at the time step 20000 with a pulse input.

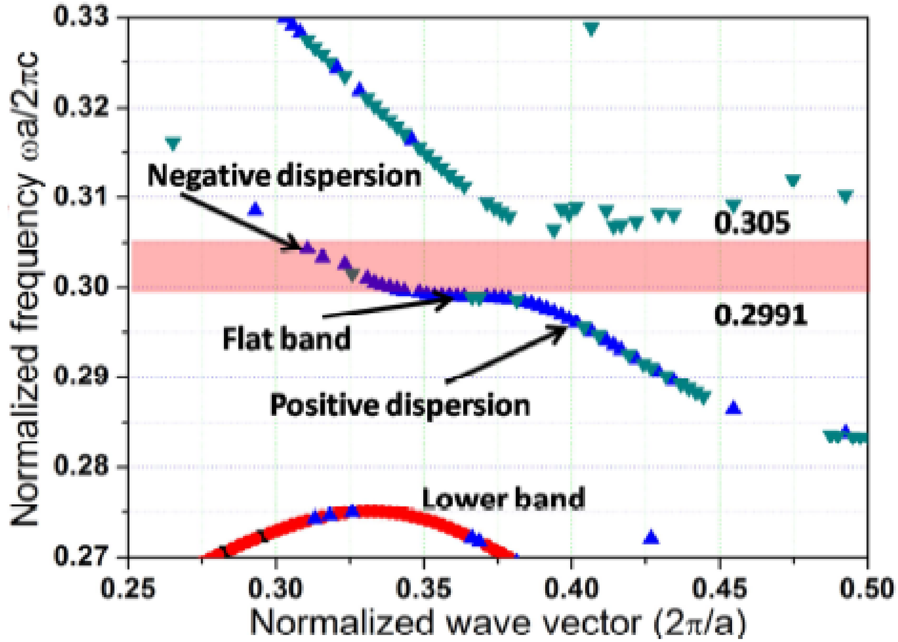


A Gaussian pulse source centered at 0.2703(2πc/a) with Δω=0.0004(2πc/a), corresponding to a 2.3nm bandwidth travels with a group index about 74.4. The relative pulse shape distortion is only 4.17%.

Slow light in chirped slot 2D PC coupled waveguide

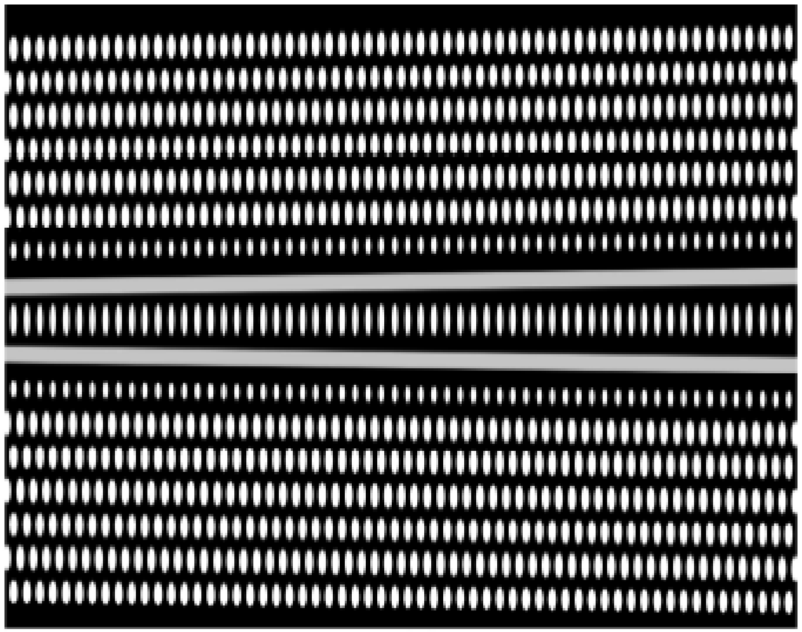


Schematic diagram of the SPCWG

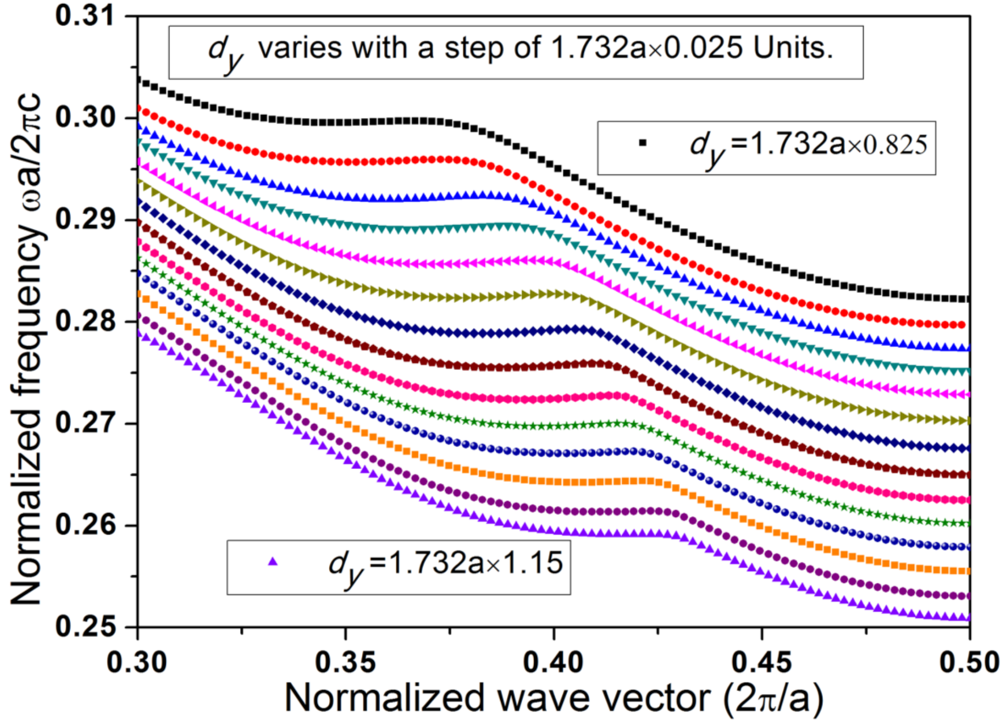


Band structure of the even mode in the electric-field component Ey (quasi-even in z direction and odd in y direction) is considered.

Chirping of dy

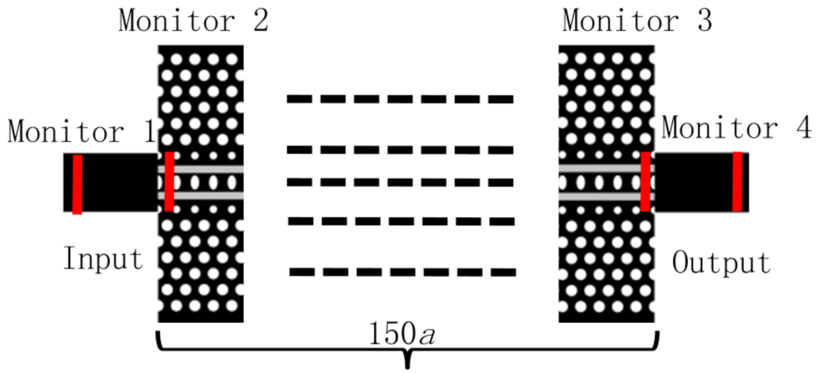


Schematic diagram of the SPCWG including chirping of dy.



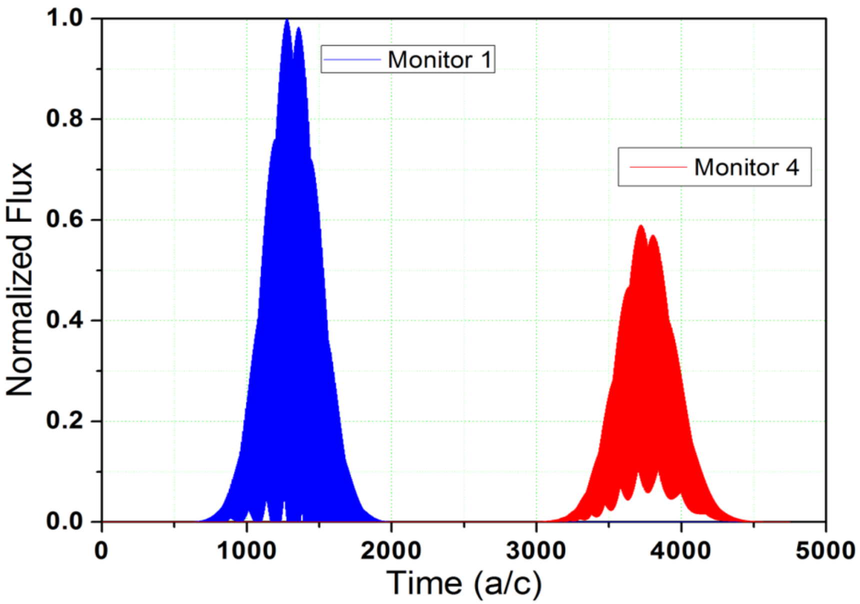
Dependence of the chair-shape-band on dy.

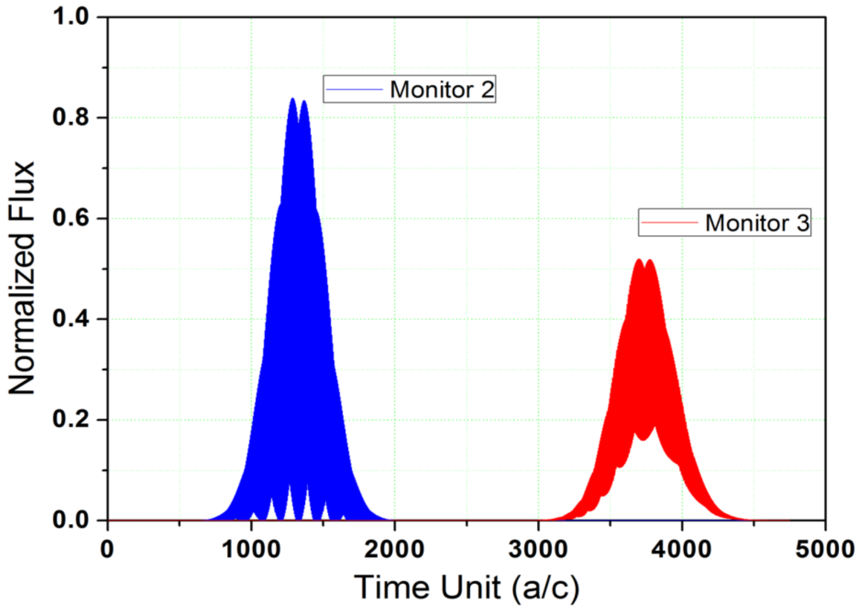
FDTD simulation of chirped slot PC coupled waveguide



Incident optical pulse: 435*a/c* (~ 0.674 ps)
output pulse: 468*a/c* (~ 0.725 ps)
Delay is ~2444*a/c* (~ 3.788 ps)

Monitor two is 439*a/c* (~ 0.681 ps)
Monitor three is 472*a/c* (~ 0.732 ps)
Delay is ~2410*a/c* (~ 3.736 ps)

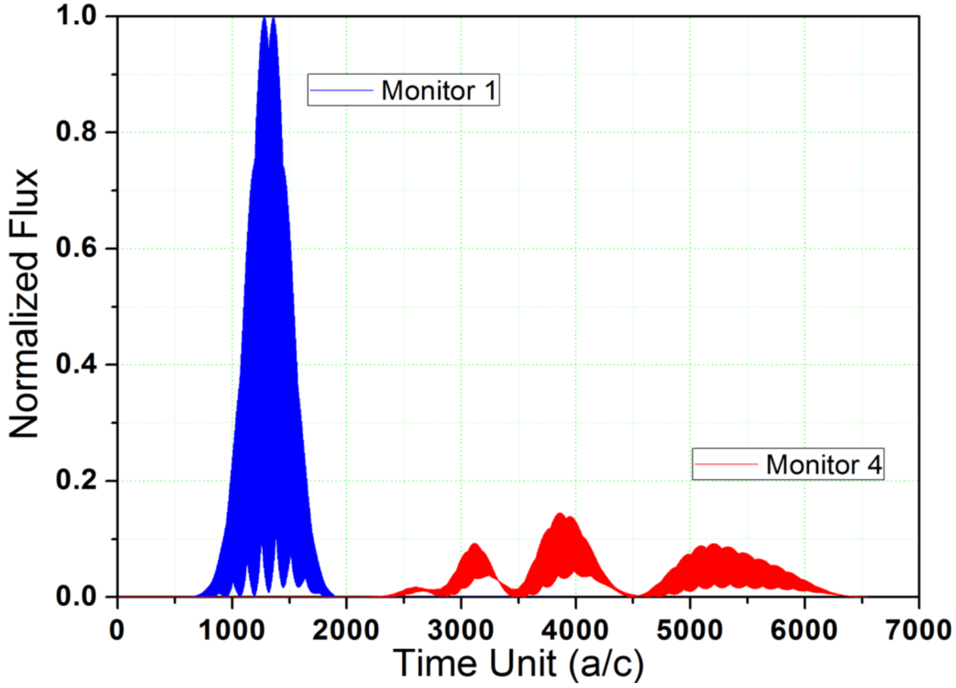


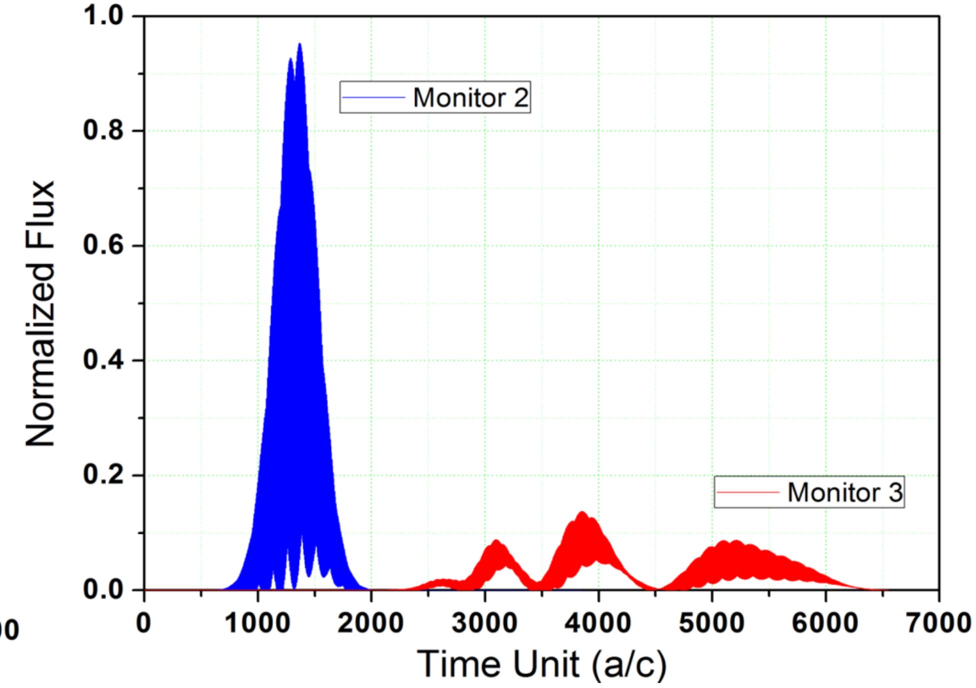


A group index is 16.067 with bandwidth of 19.7nm.

FDTD simulation of unchirped slot PC coupled waveguide

The same incident optical pulse is used.

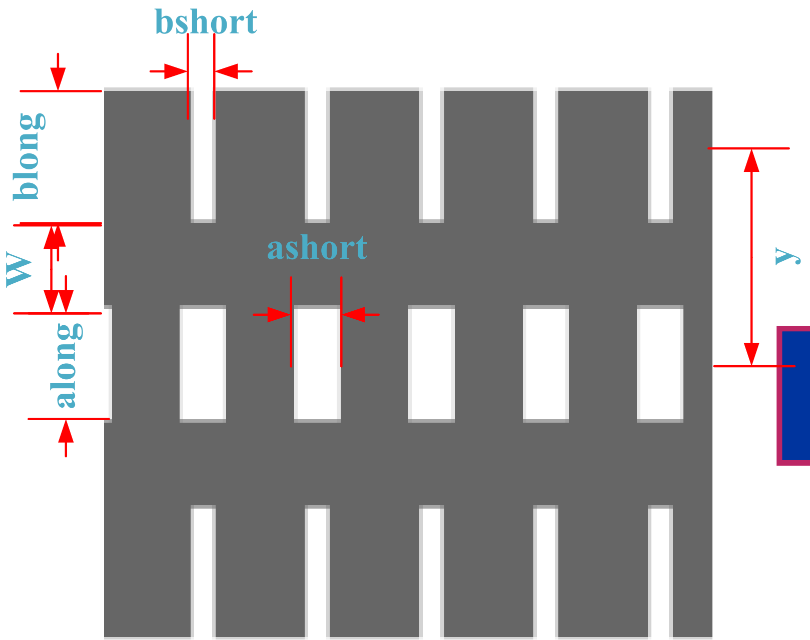




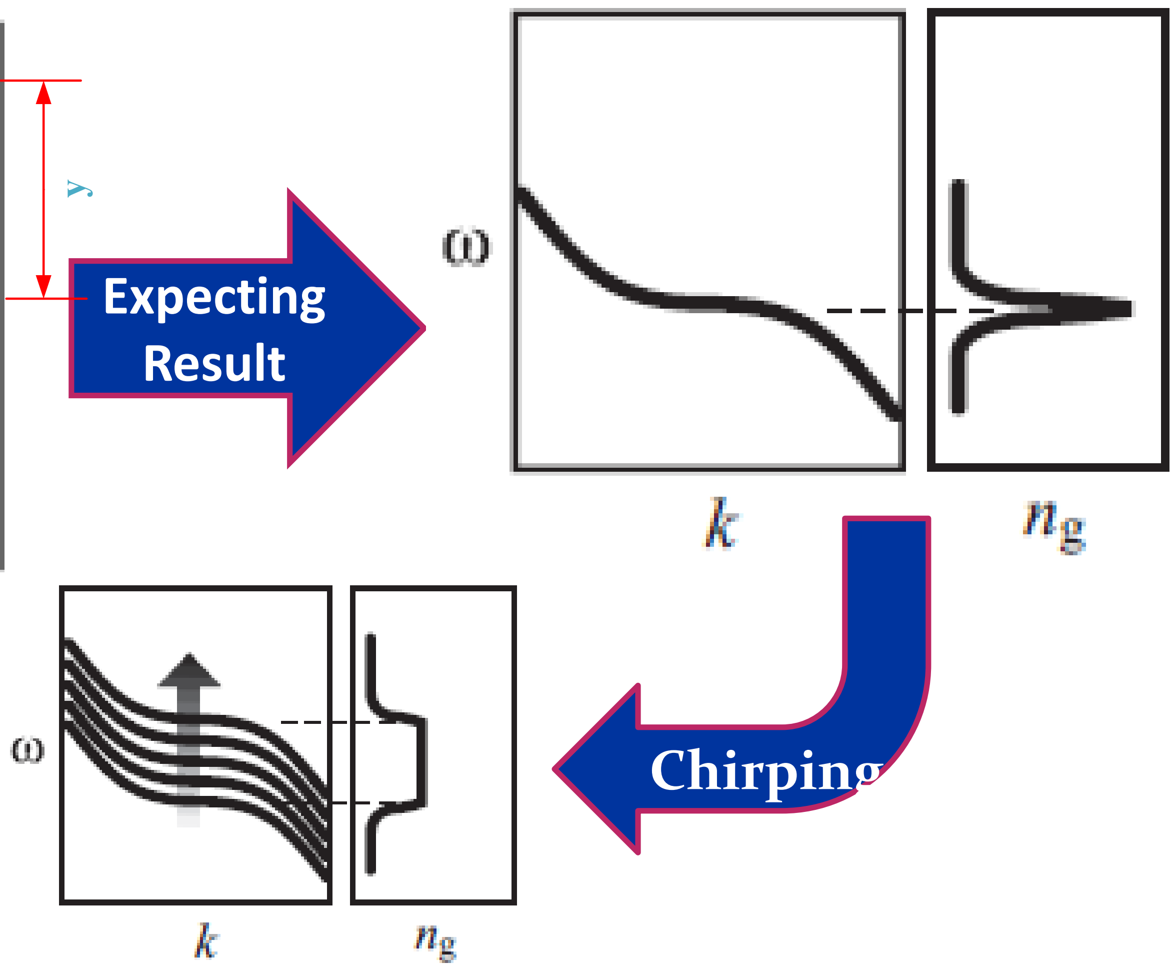
Pulse propagations with various chirp ranges of $\boldsymbol{d_y}$

The entire chirp length of the SPCWG is 150*a*				
Chirp range of $d_y \times 1.732\, a$	**Bandwidth for center wavelength 1550nm** **nm**	**Average Group index**	**Group index bandwidth product**	**Relative pulse shape expansion at Monitor 3 compared with Monitor 2**
0.835 to 0.865	19.7	16.06	316.38	7.52 %
0.84 to 0.86	13.1	20.3	265.93	6.02 %
0.845 to 0.855	6.5	29.1	189.15	5.15 %
0.8475 to 0.8525	3.26	40.23	131.15	5.24 %
0.849 to 0.851	1.3	48.5	63.05	5.15 %

Slow light in 1D chirped waveguides

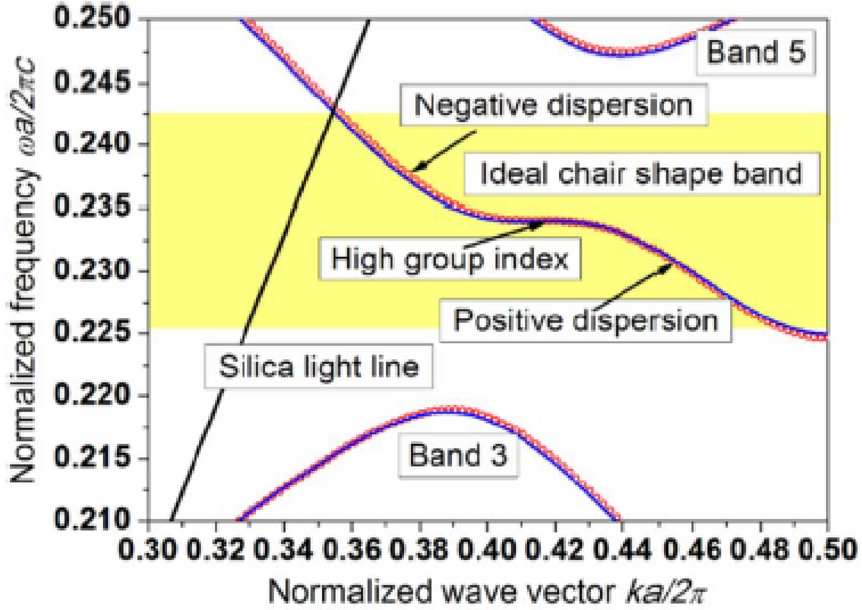


Proposed Structure.

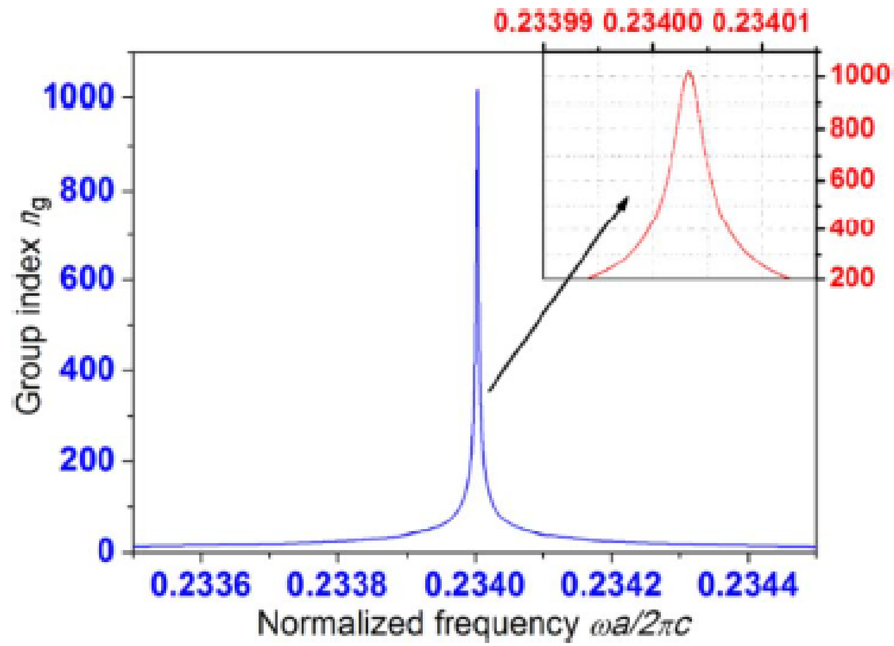


Broad Band Slow light

Group index characteristics of 1D waveguide



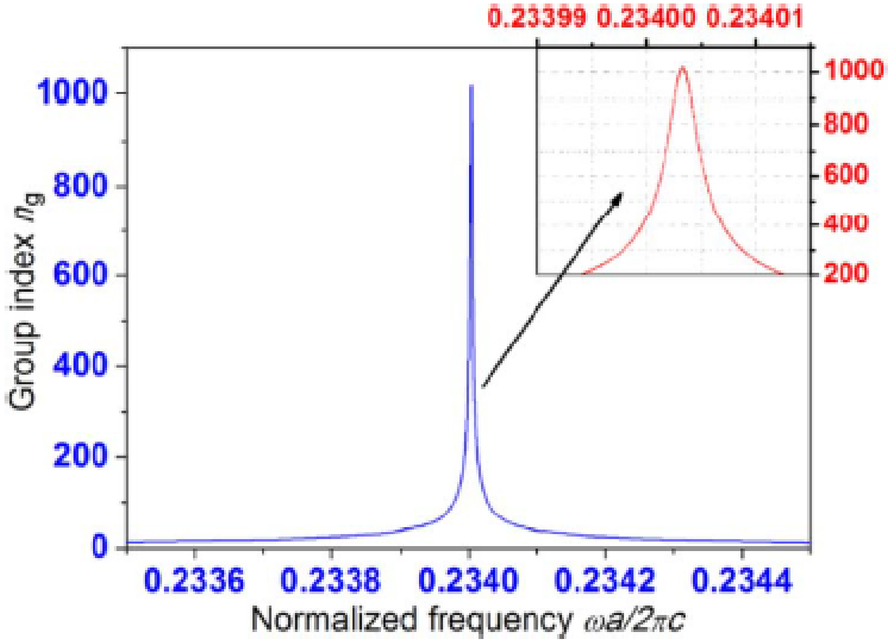
Comparison of the same band calculated by the PWE and FDTD.



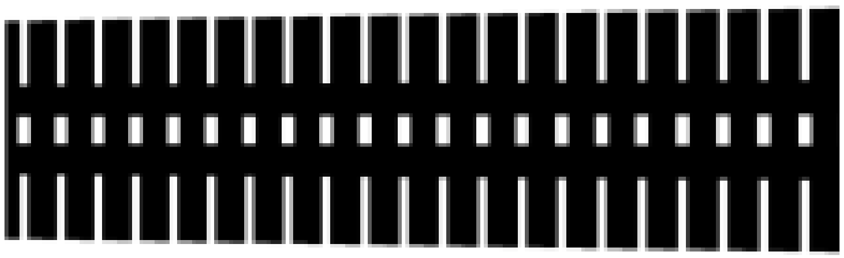
Group index characteristics

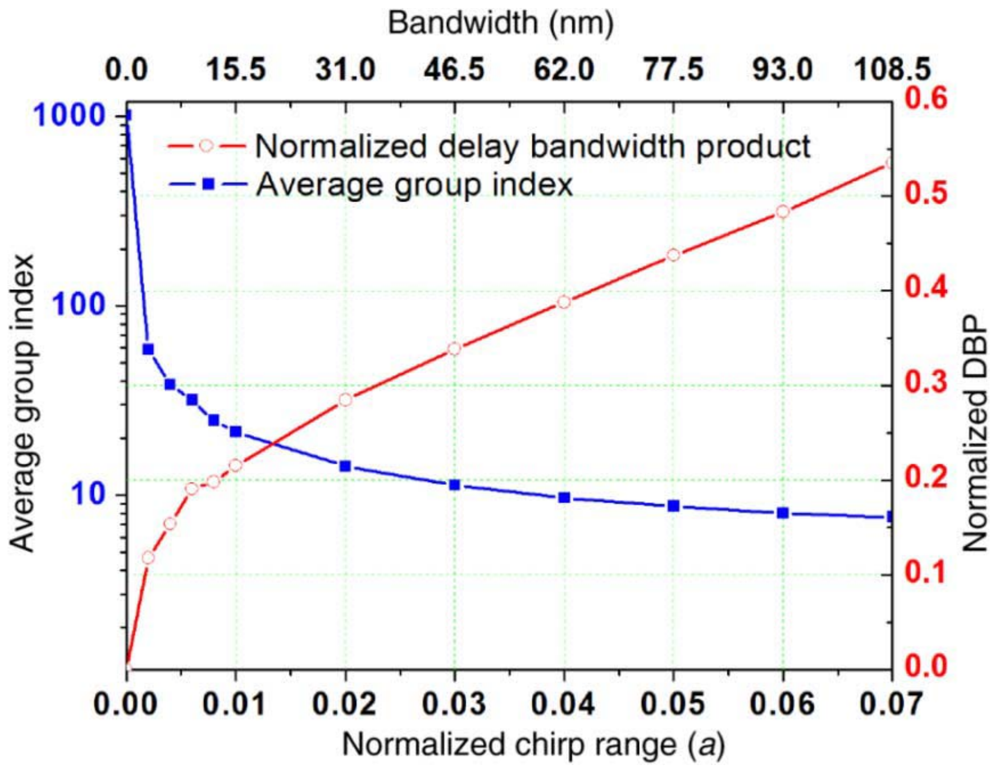
Parameters are with ashort=0.3, along=0.8, bshort=0.2,blong=1.75, wWhole=6, and w=0.85.

Chirping 1D waveguide by scaling law



Group index characteristics

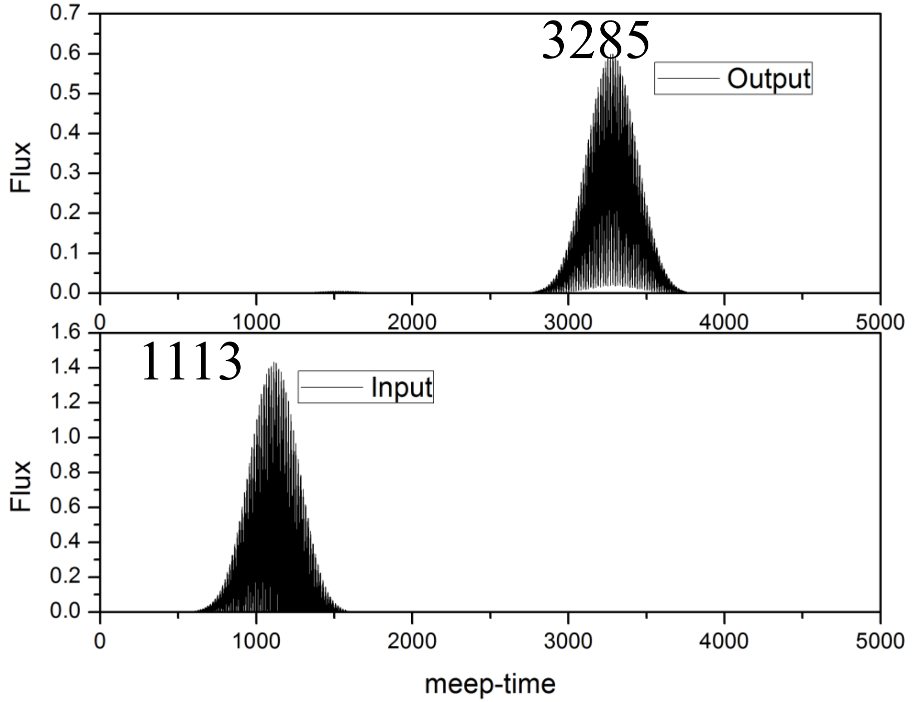




Average group index and normalized DBP as a function of the normalized chirp range and the corresponding slow light bandwidth

FDTD simulation of the chirped 1D WG

Schematic of Chirp of 150 period from 0.7a to 1.3a



Practically, chirp from **0.99a to 1.01a**

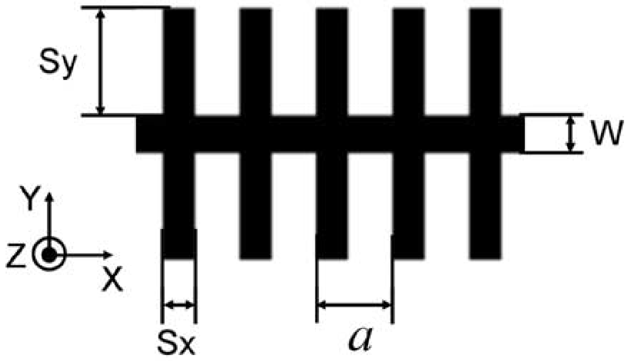
Input Position=73.98a

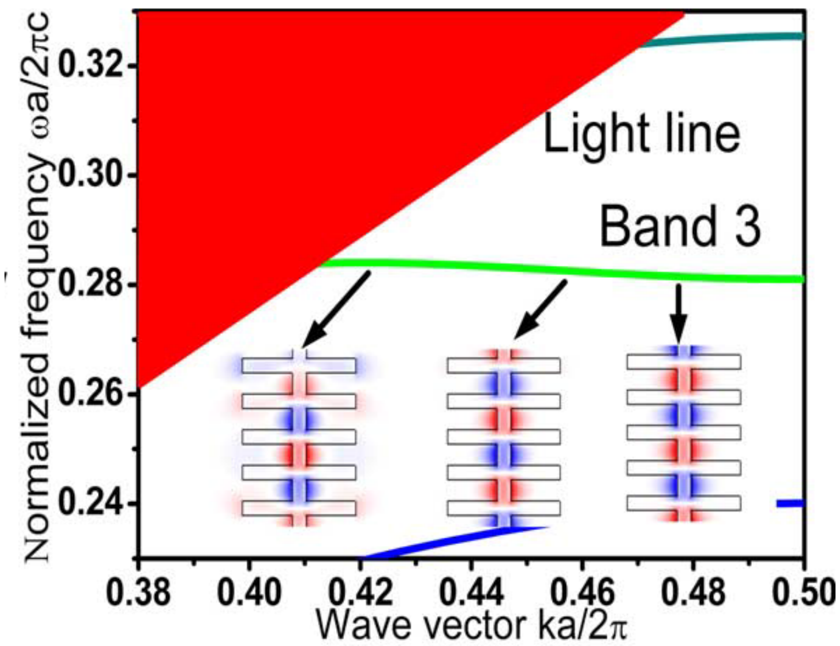
Output Position=-74.2a

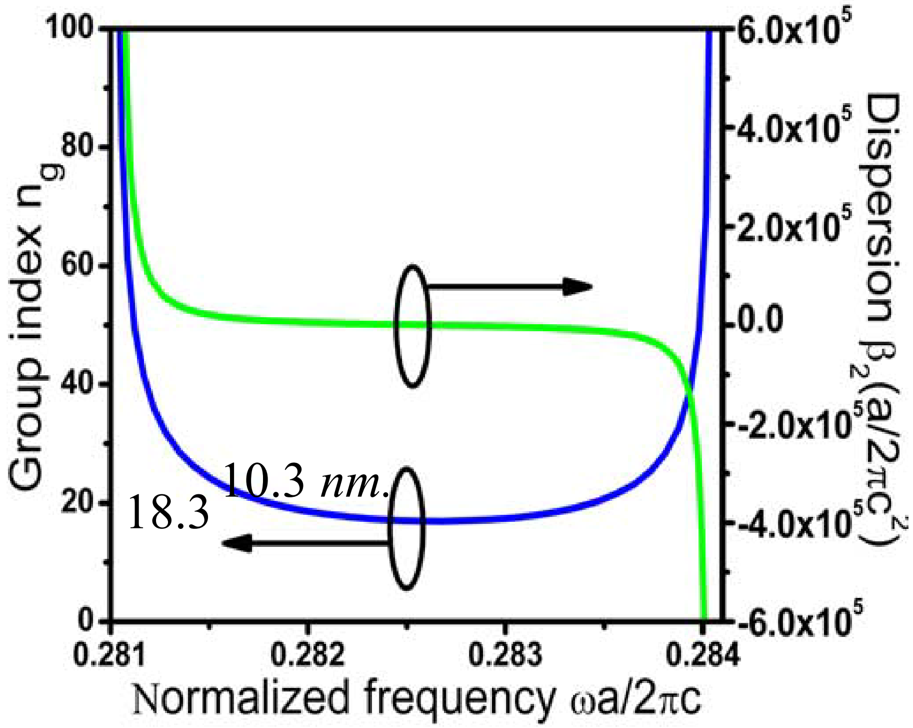
df	0. 0046
centerF	0. 234000031
n_g	14. 675
Bandwidth	30. 47008143nm

The relative pulse expansion is **2.34%**.

Slow light in a silicon grating waveguide

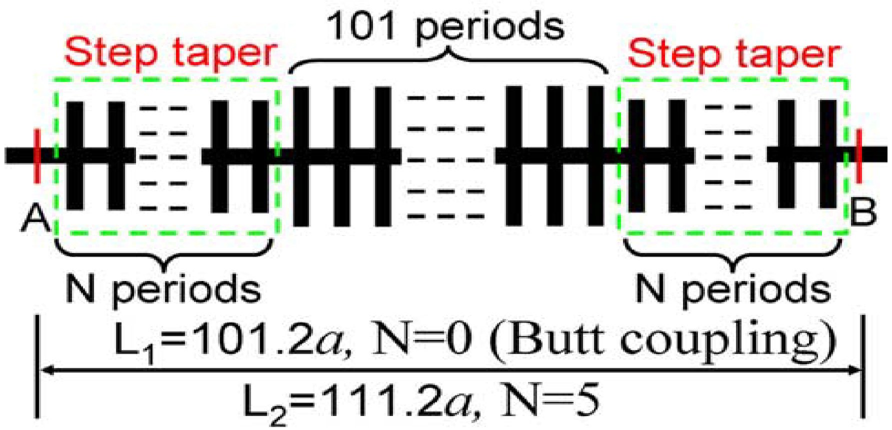


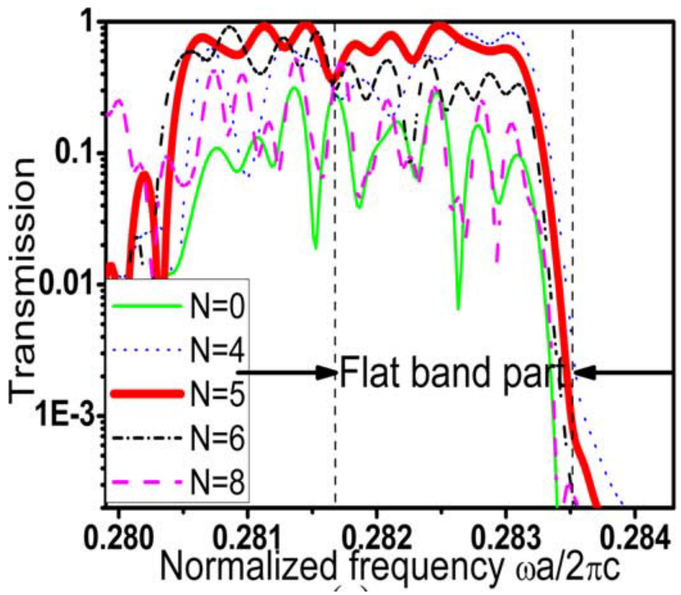


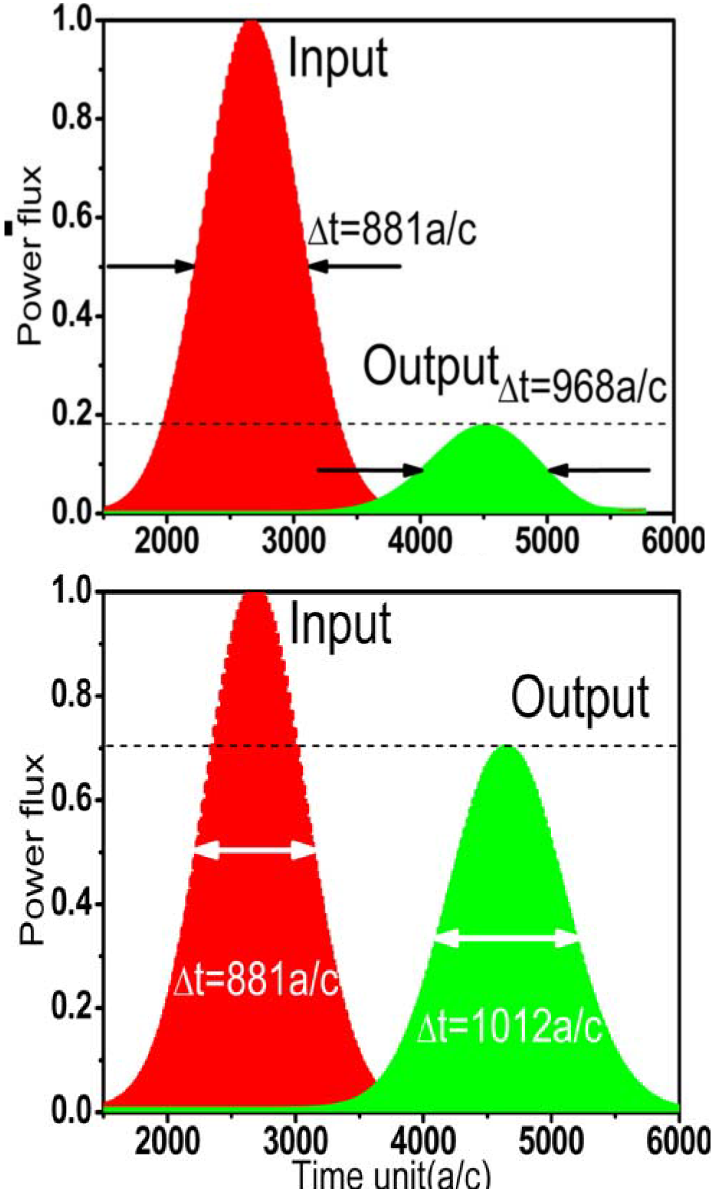


Sx=0.4a, Sy=1.8a, W=0.5a

FDTD results







Group index is 17.54. the bandwidth is about 10.3 nm.

SUMMARY

Wide band slow light can be implemented in both 2D and 1D structures.

- **From 2D periodic structure**
  - → **2D chirping structure**
- **From 2D structures**
  - → **1D structures**
- **From Bandgap structures**
  - → **Total internal reflection structures**

Perspective

How is the slow light loss in 1D structures?

THANKS FOR YOUR ATTENTION!

ANY QUESTIONS?