Nonlinear Optical Phenomena in Periodic Structures

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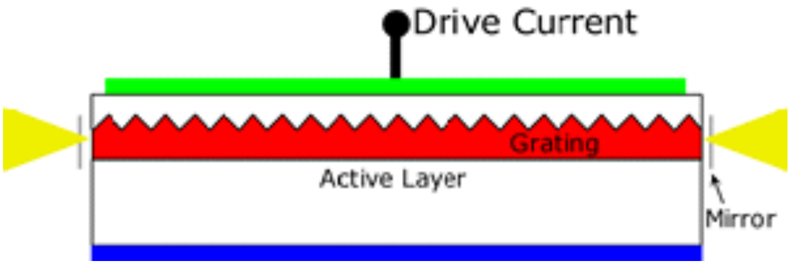
From Ghana to the Birthplace of Nonlinear Optics

Met Valentina Tereshkova in January 1964!

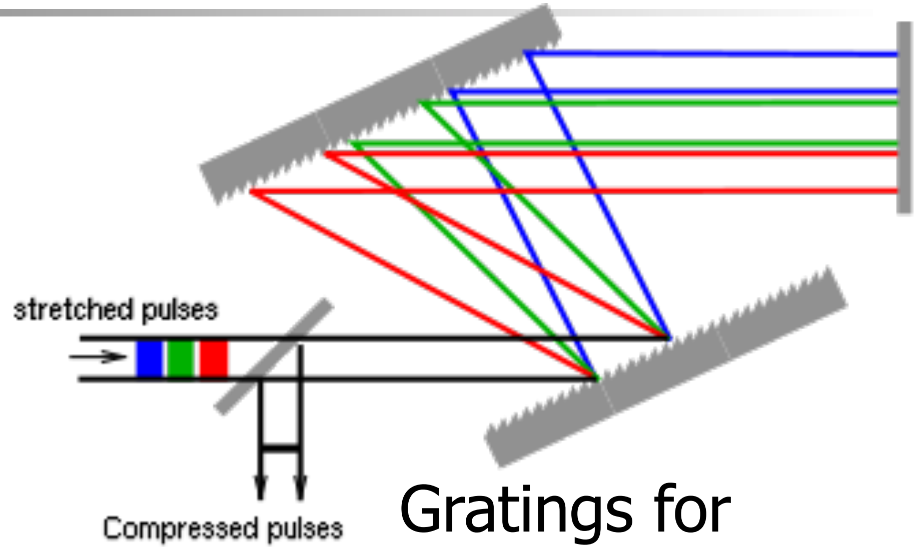
Outline

- Periodic structures in optics
- Inclusion of the nonlinear index
- Optical bistability and gap solitons
- Self-pulsing
- Pulse compression and Bragg solitons
- Raman gap solitons
- Distributed-feedback Raman lasers
- Conclusions

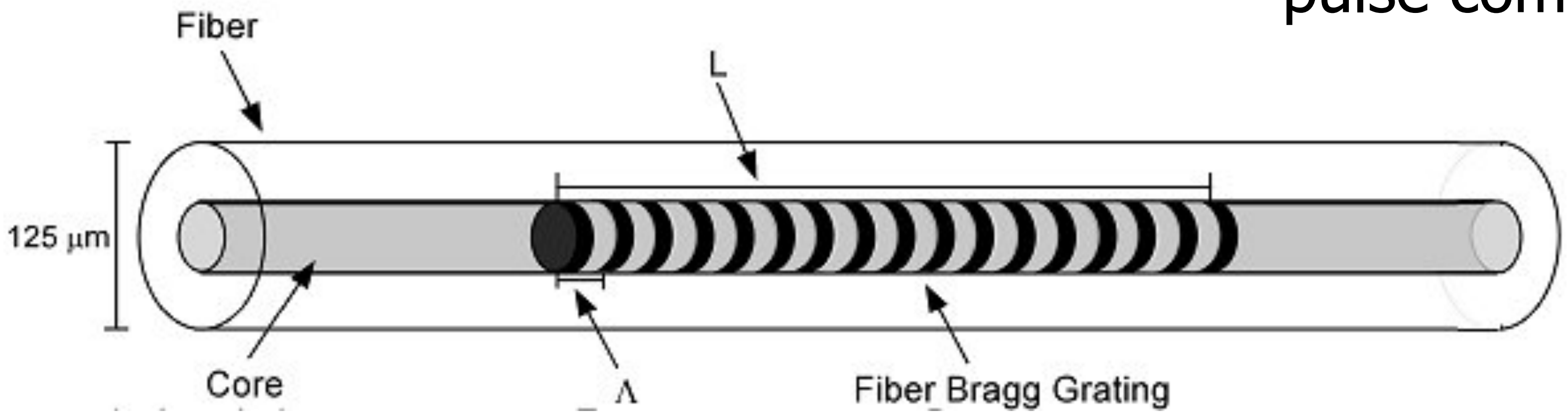
Periodic structures in optics



DFB laser: Kogelnik & Shank

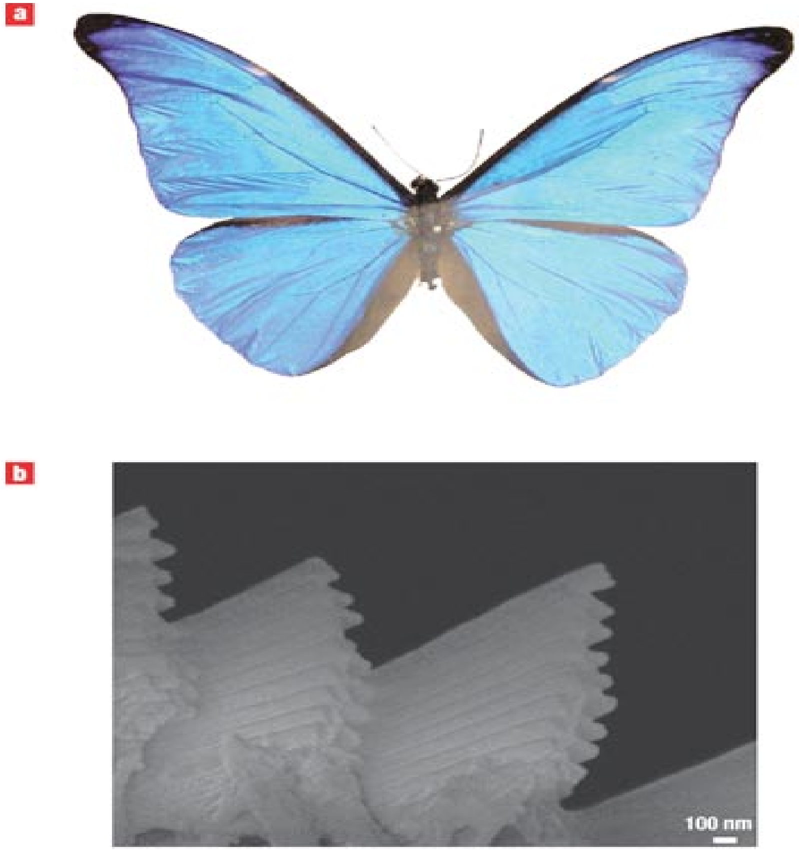


Gratings for
pulse compression

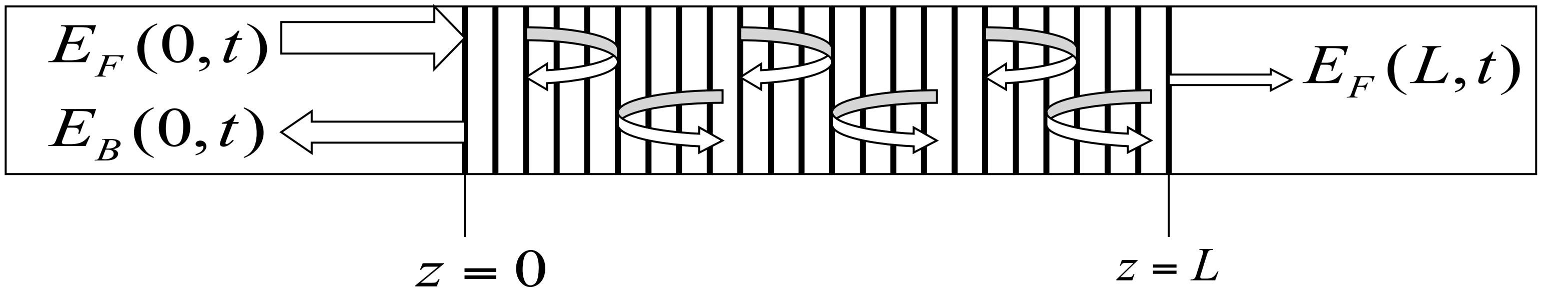


Periodic structures in nature

- Colors of butterfly wing arise from Bragg reflections off periodic nanostructures



1-D Photonic Bandgap Structure



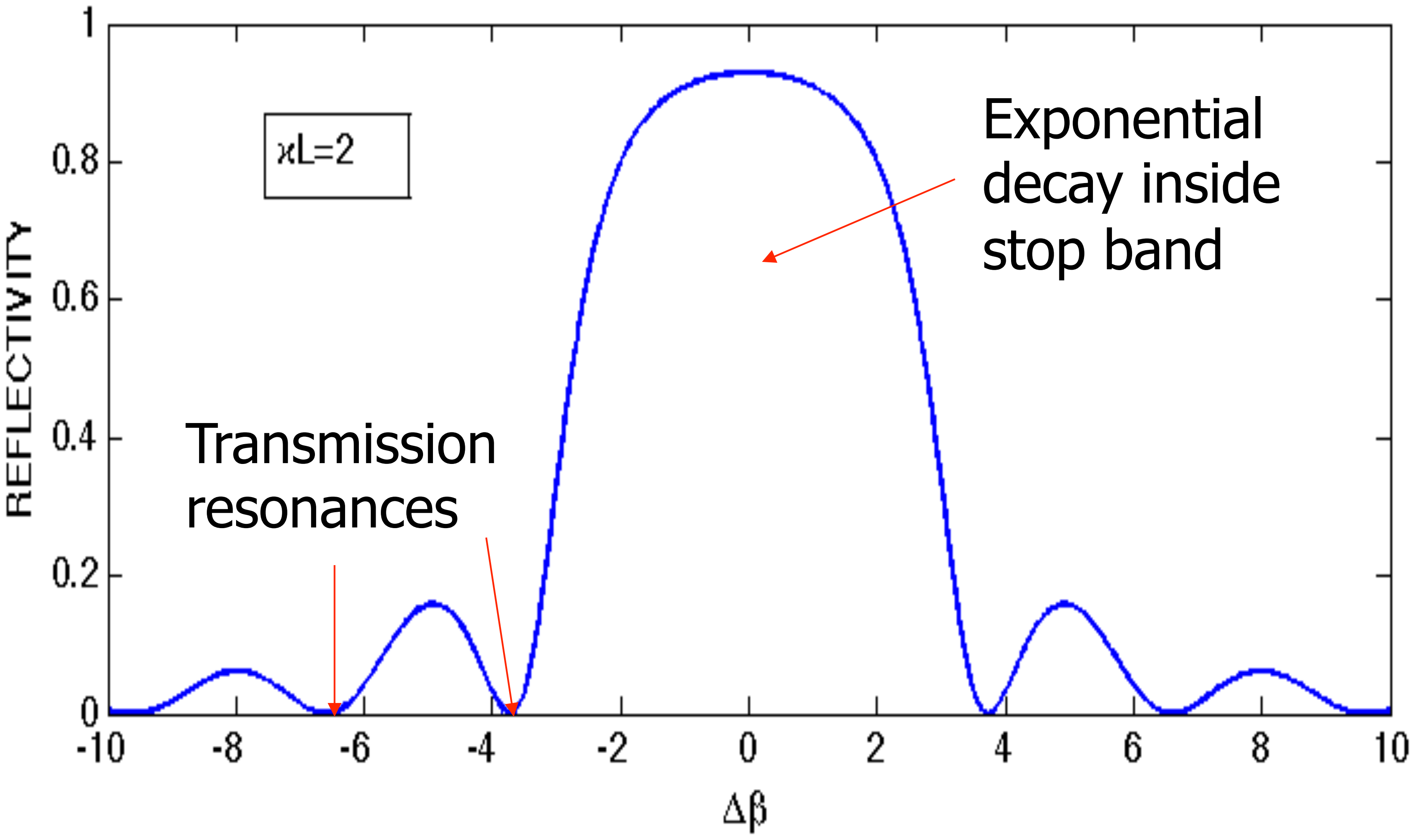
$$n = n_0 + \Delta n \cos(2\beta_0 z)$$

Grating coupling constant $\kappa = \pi \Delta n / \lambda_B$

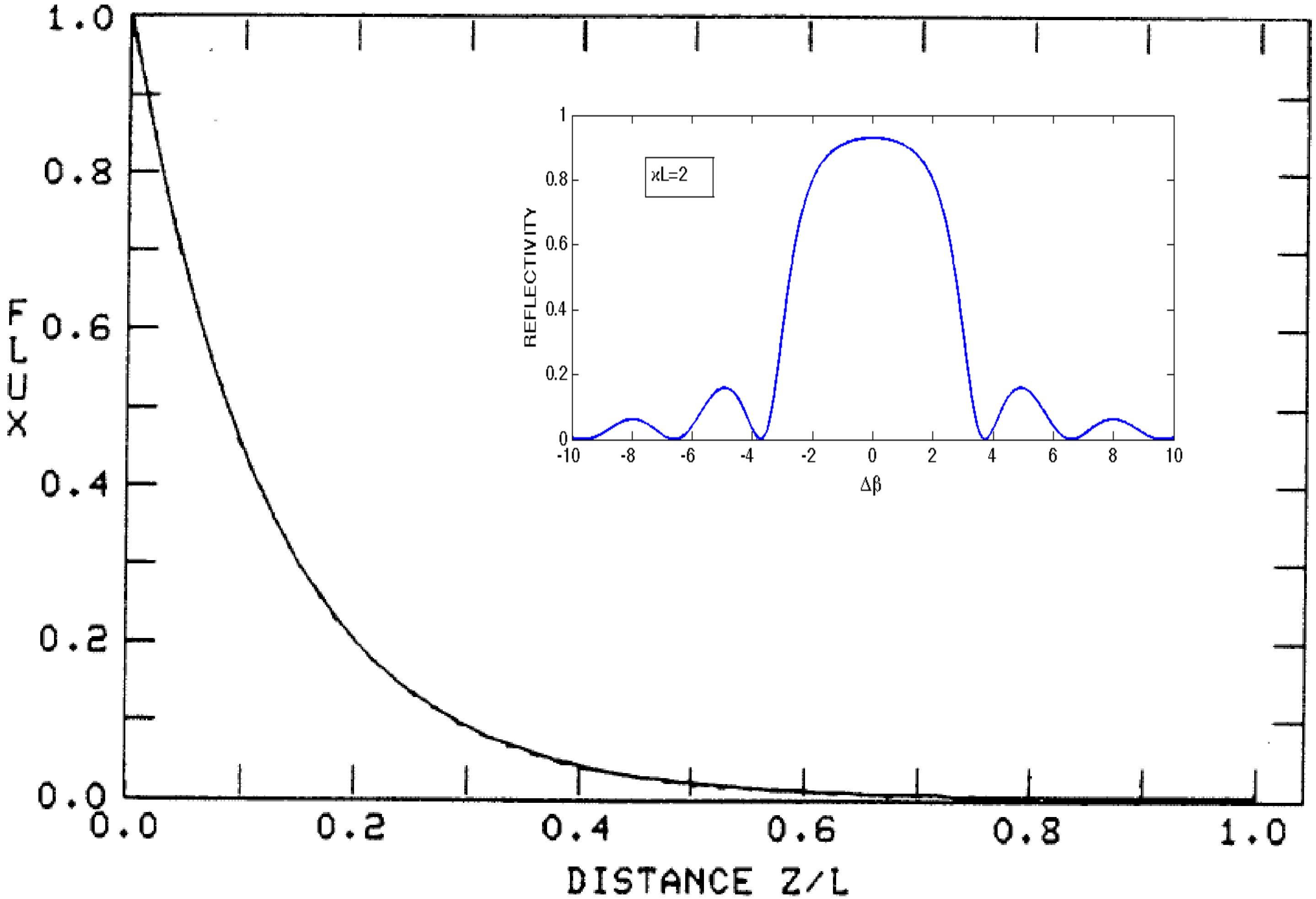
Bragg wavelength $\lambda_B = 2\pi n_0 / \beta_0$

Detuning $\Delta\beta = \beta - \beta_0$

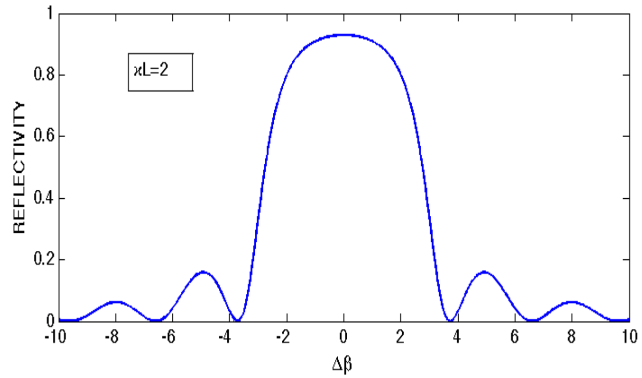
Reflectivity of Bragg grating

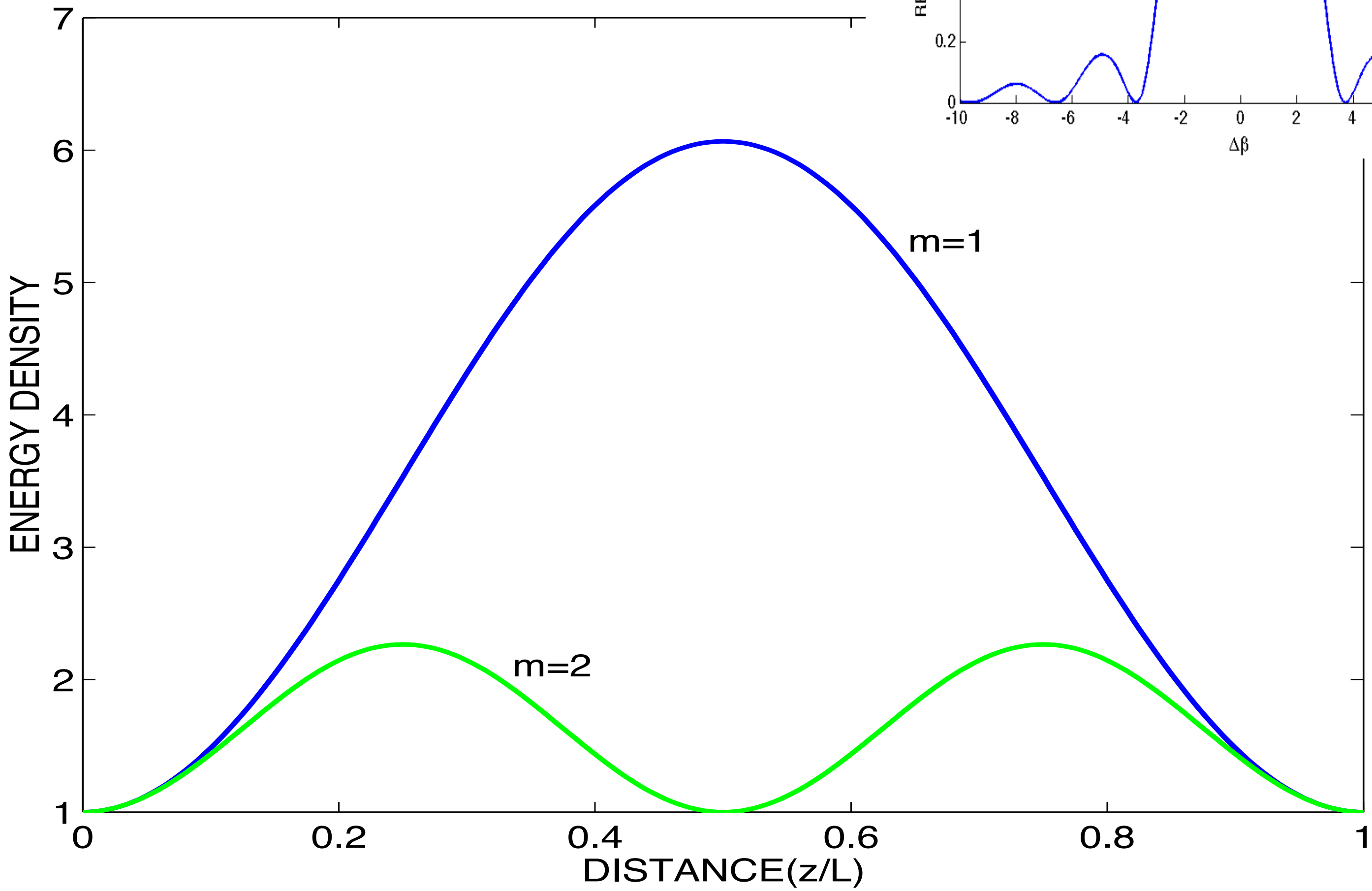


Intensity distribution in stop band



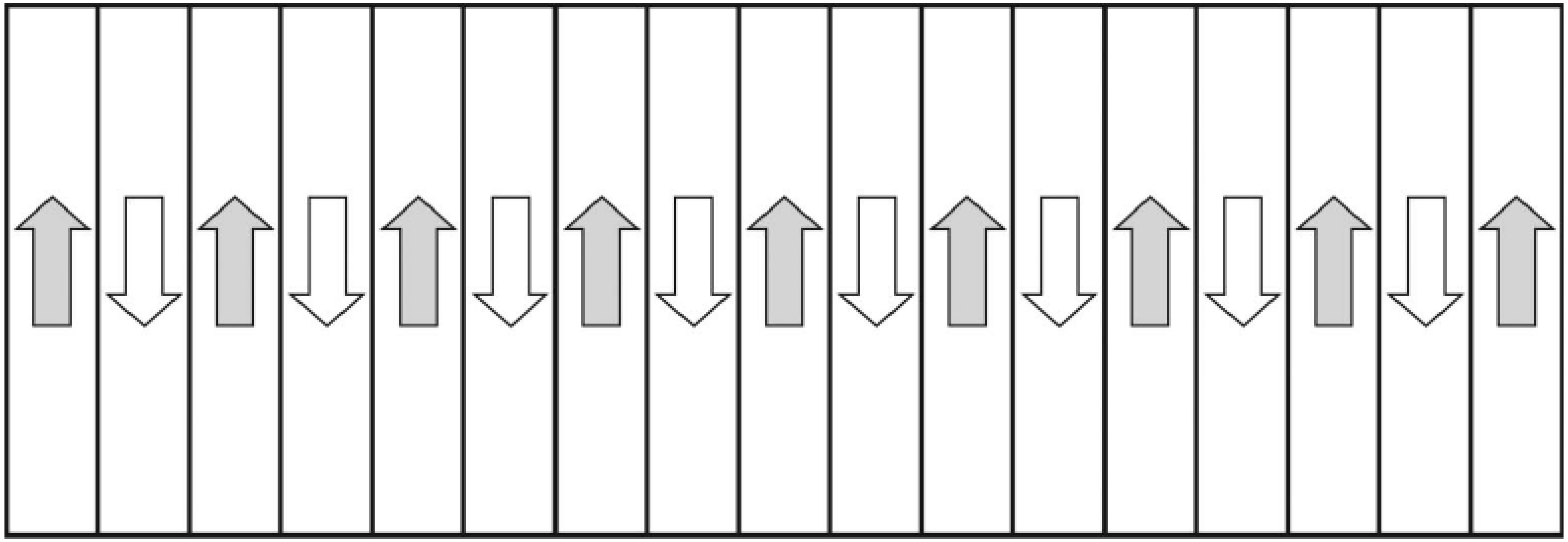
Intensity distribution at resonances





Periodic structures in nonlinear optics (pre 1979)

1962: Armstrong et al propose quasi-phase matching by periodic reversal of crystal optic axis. [Also, Alan Hill, 1961!]



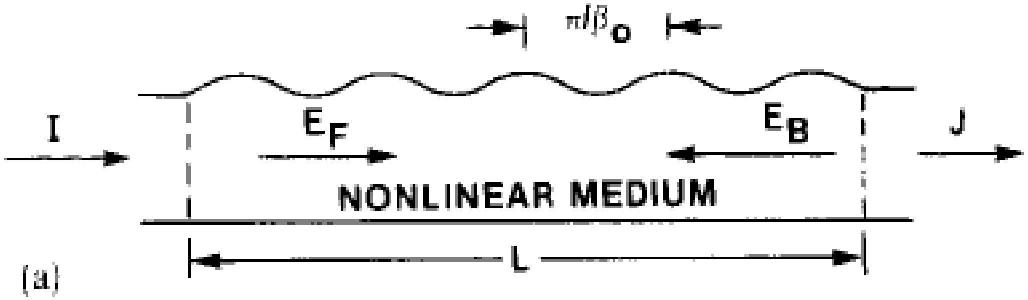
Inclusion of nonlinear index in periodic structures (1979)

- What if a periodic structure had an intensity-dependent refractive index?

$$n = n_0 + \Delta n \cos(2\beta_0 z) + n_2 I$$

- Should enable intensity-tuning of stop band, switching, optical bistability (*Winful, et. al Appl. Phys Lett. 35, 379 (1979)*)

Nonlinear coupled-mode equations



$$\frac{dE_F}{dz} = i\kappa E_B e^{-i2\Delta\beta z} + i\gamma\left(\left|E_F\right|^2 + 2\left|E_B\right|^2\right)E_F$$

$$\frac{dE_B}{dz} = -i\kappa E_F e^{+i2\Delta\beta z} - i\gamma\left(\left|E_B\right|^2 + 2\left|E_F\right|^2\right)E_B$$

Nonlinearity $\gamma = \pi n_2 / \lambda_B$

Elliptic function solution

$$\boxed{I = \frac{J}{1 + [y_- / y_+] sn^2[-y_+ \mid (y_- / y_+)^2]}}$$

where

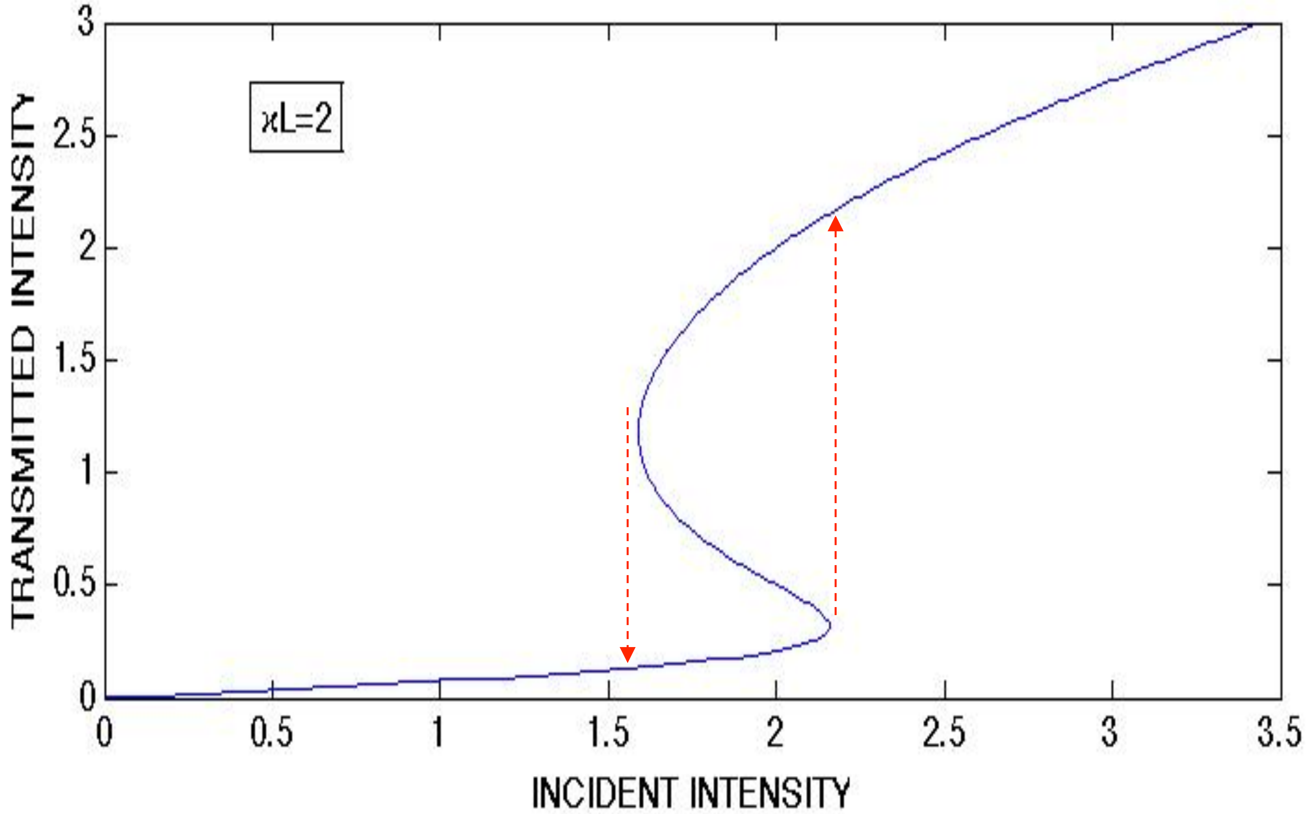
$$y_\pm = J / 2 \pm [(\kappa L)^2 + (J / 2)^2]$$

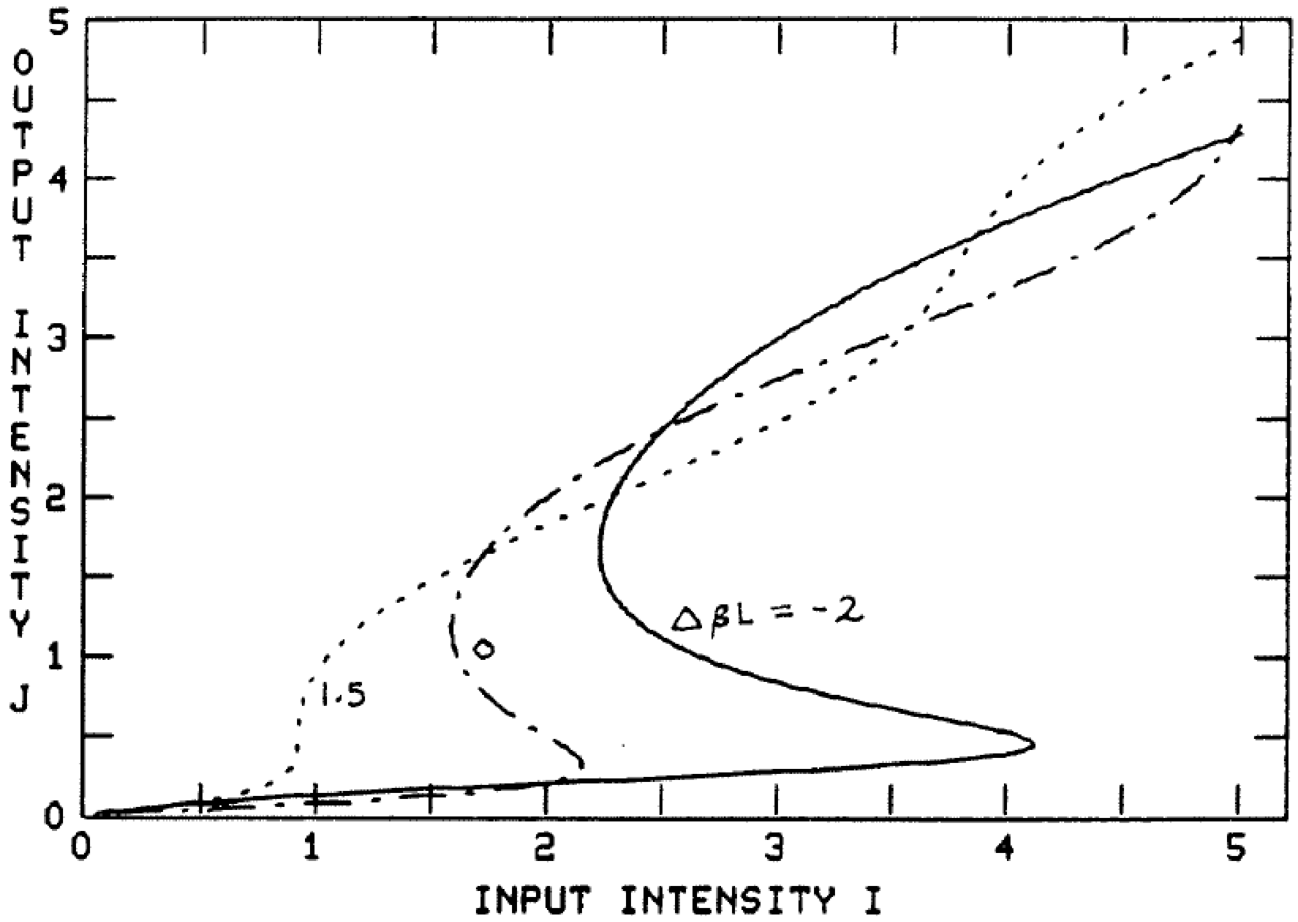
Theory of bistability in nonlinear distributed feedback structures

Herbert G. Winful, J. H. Marburger, and E. Garmire
Center for Laser Studies, University of Southern California, University Park, Los Angeles, California 90007

(Received 29 May 1979; accepted for publication 19 June 1979)

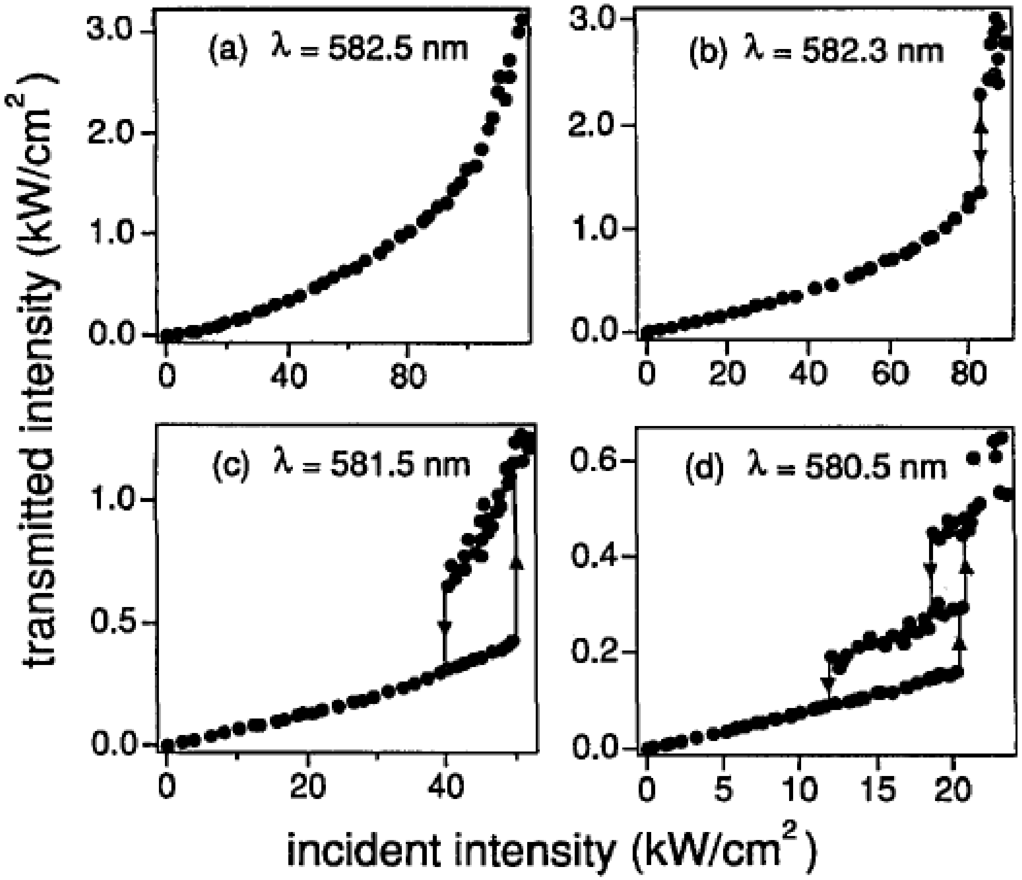
We show that optical bistability can occur in a distributed feedback structure with an intensity-dependent refractive index. Analytical expressions for the transmissivity are obtained and a comparison with Fabry-Perot-type devices is presented.




OUTPUT INTENSITY J
INPUT INTENSITY I
0
1
2
3
4
5
1.5
0
ΔβL = -2

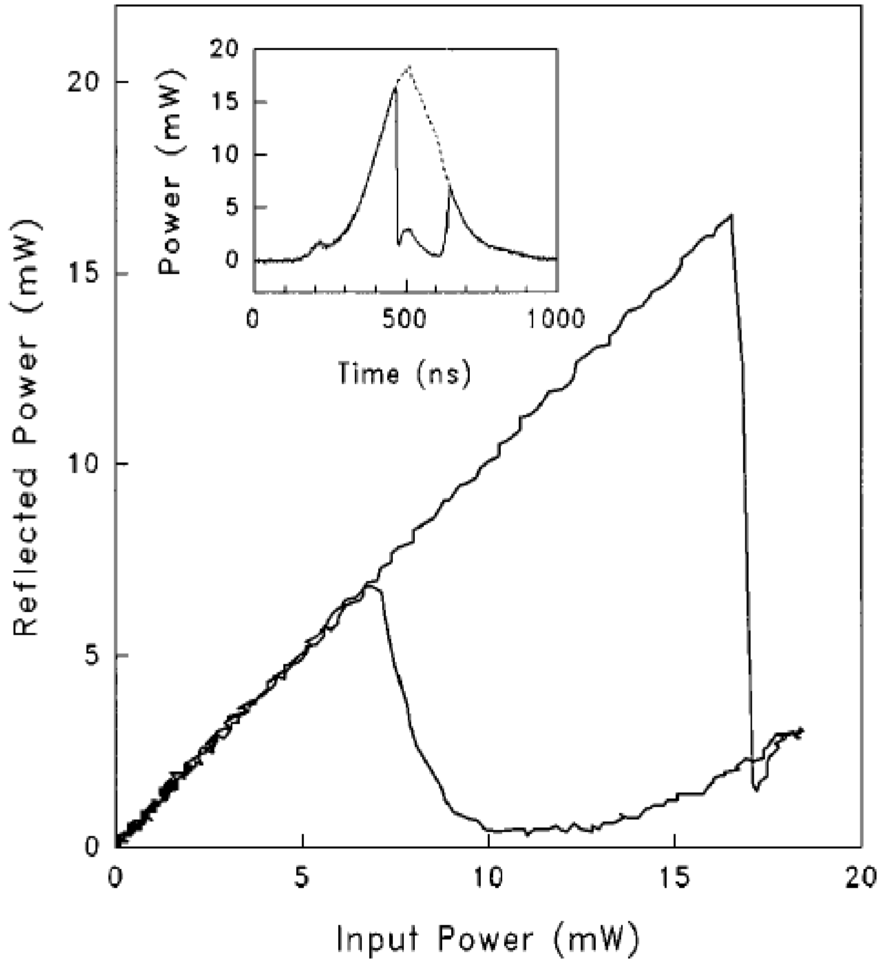
Bistability in periodic structures: experiments

- C. J. Herbert and M. Malcuit, Opt. Lett. 18, 1783 (1993)
- Used colloidal crystal with periodic planes
- Nonlinearity was thermal in origin

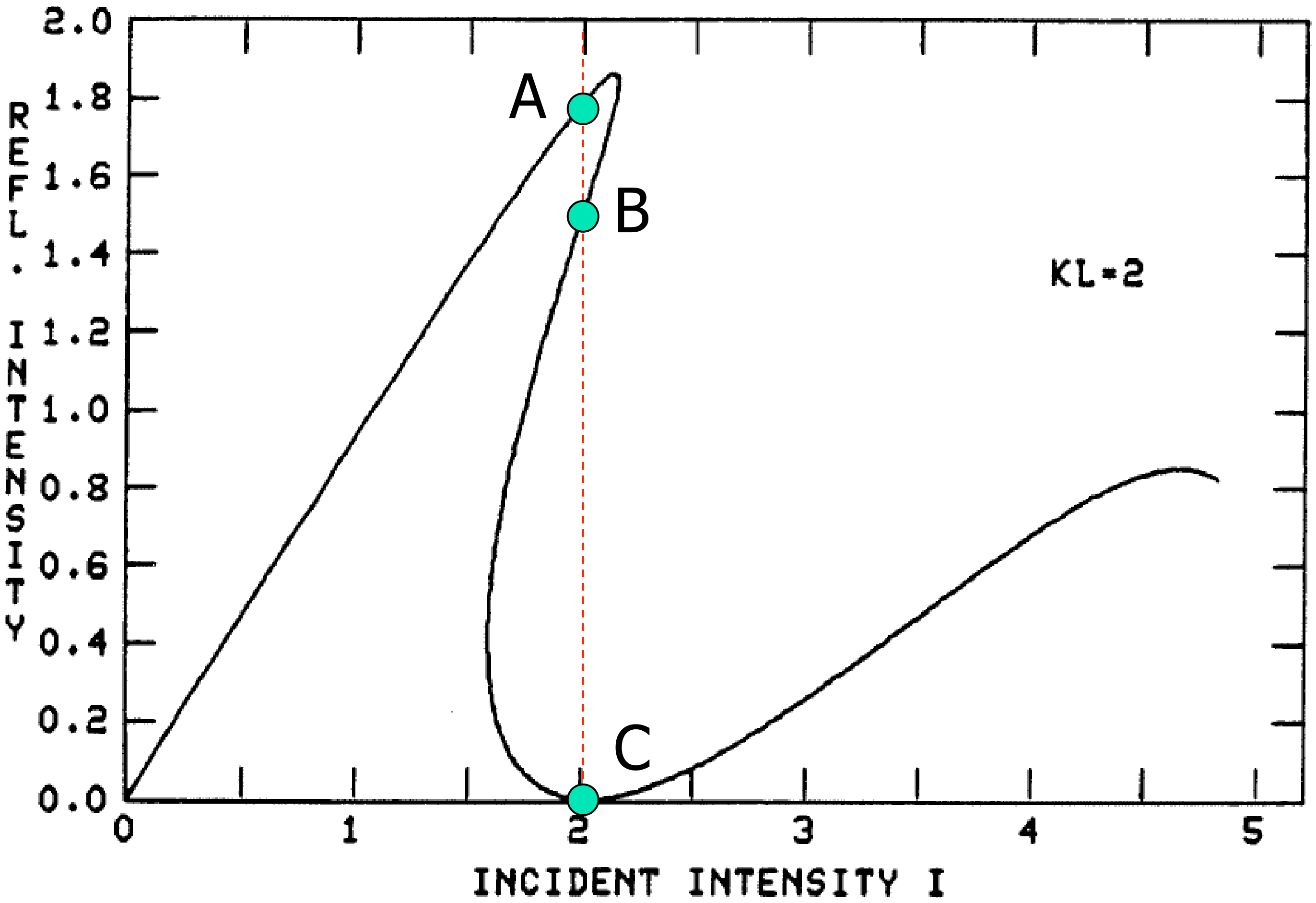


Bistability in periodic structures: experiments (cont.)

- S. Janz, et al Appl. Phys. Lett. 67, 1051 (1995)
- GaAS/AlGaAs quarter-wave shifted DFB structure
- 200 ns pulses, 1km/cm^2

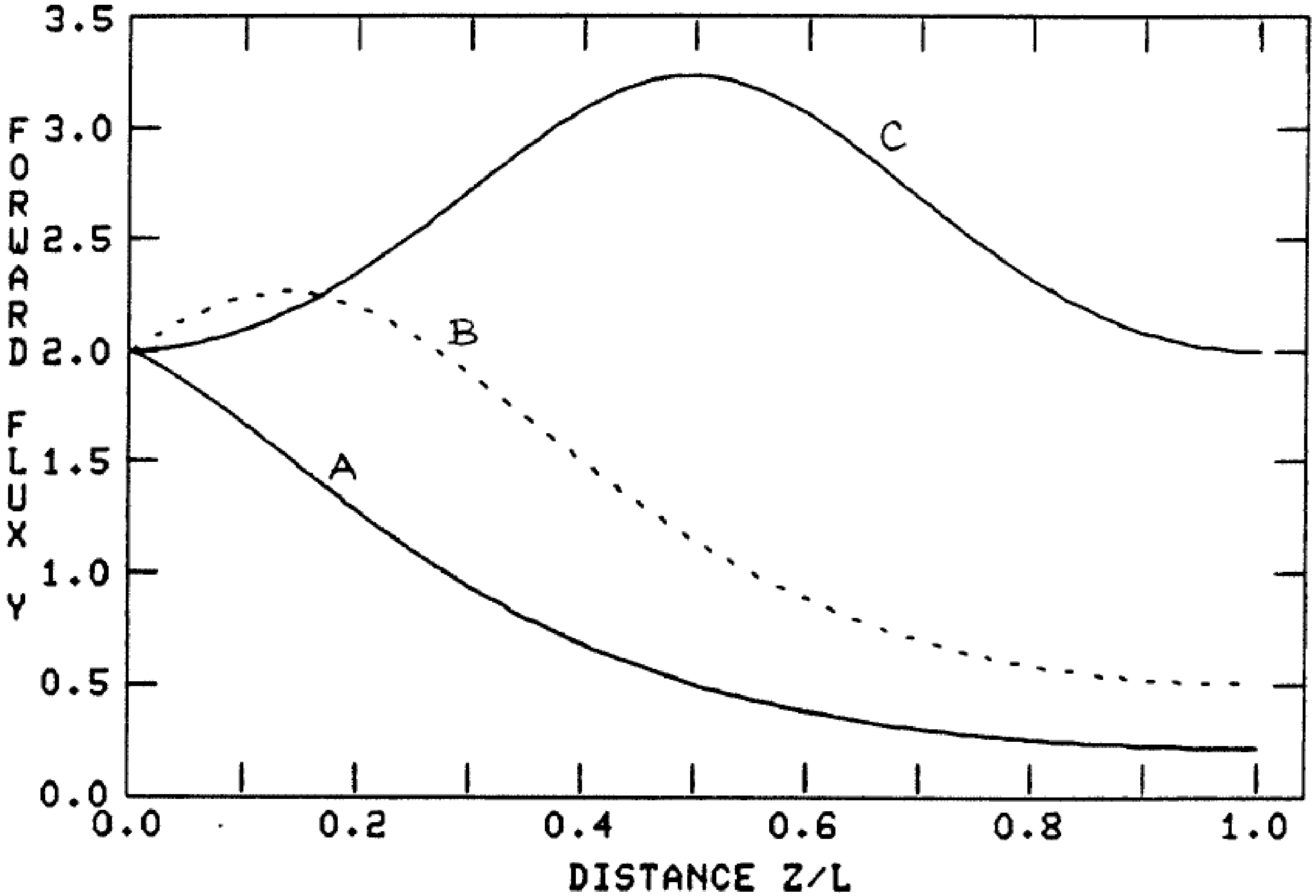


Nature of multiple solutions



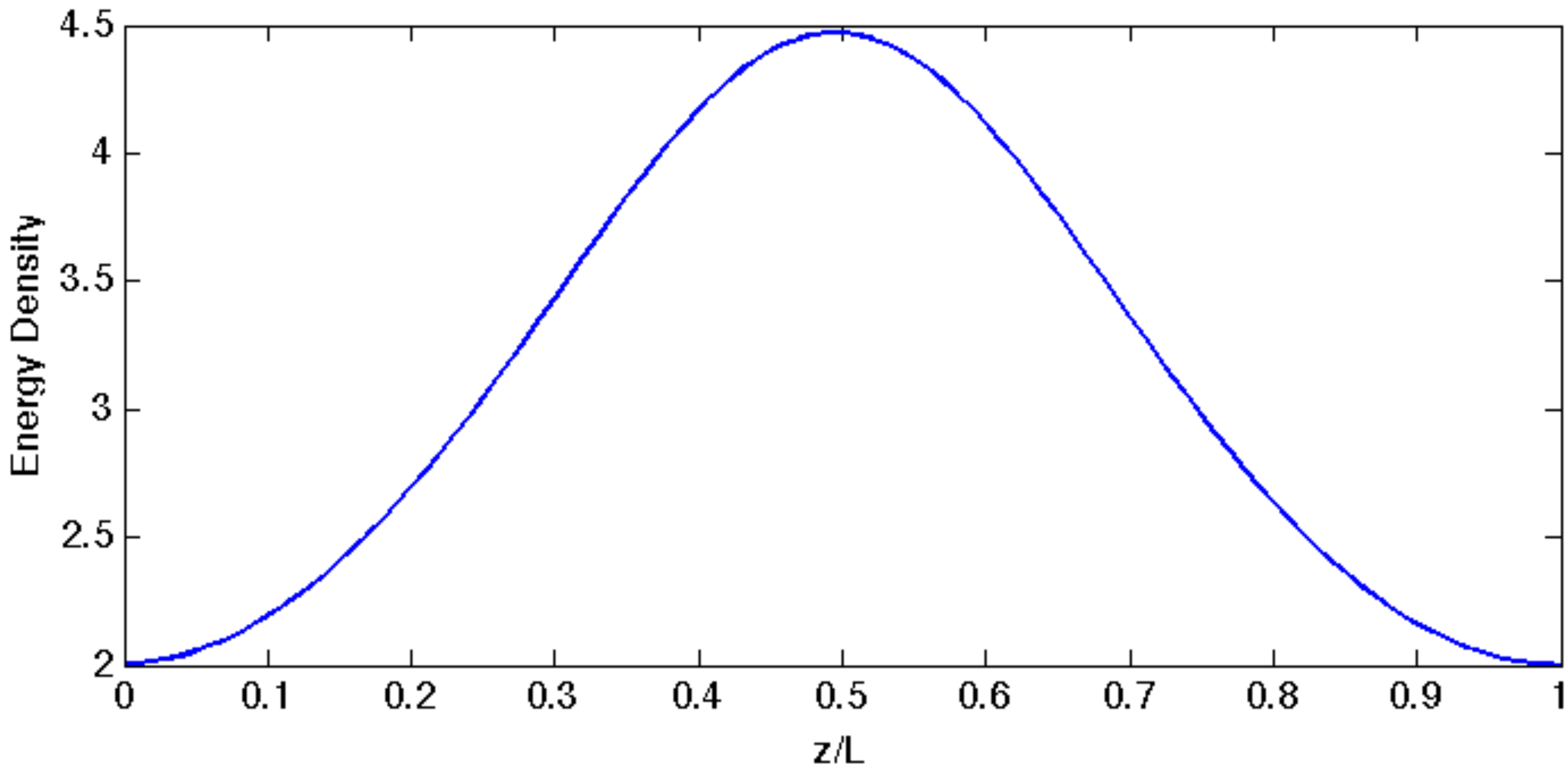
Total transmission solution

H.Winful, PhD dissertation, USC 1980



Gap soliton: total transmission solution

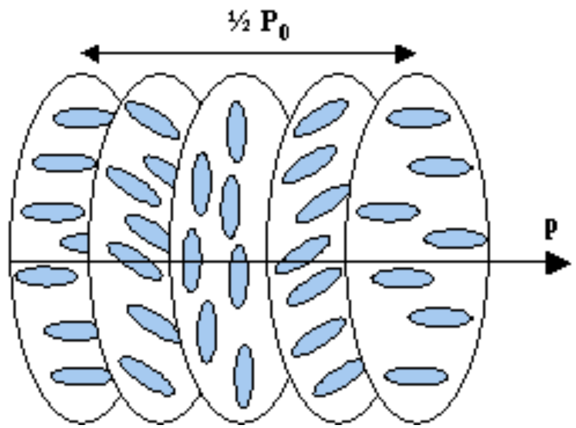
- Static sech field distribution for intense field tuned inside band gap (*Winful, 1980; Chen and Mills, 1987*)

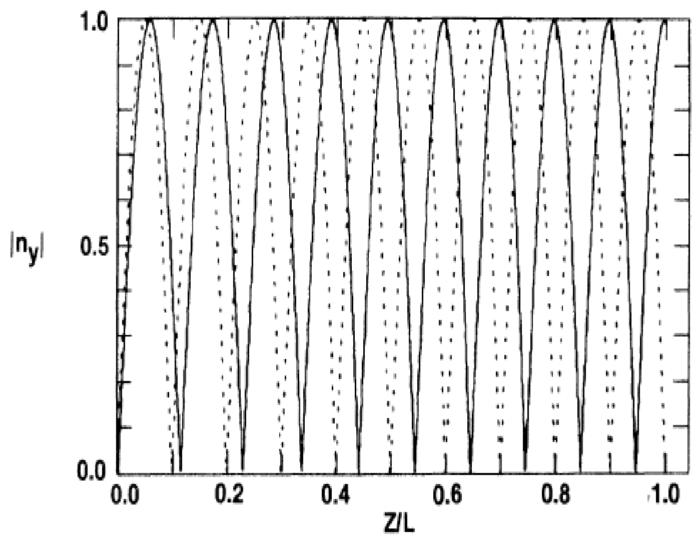


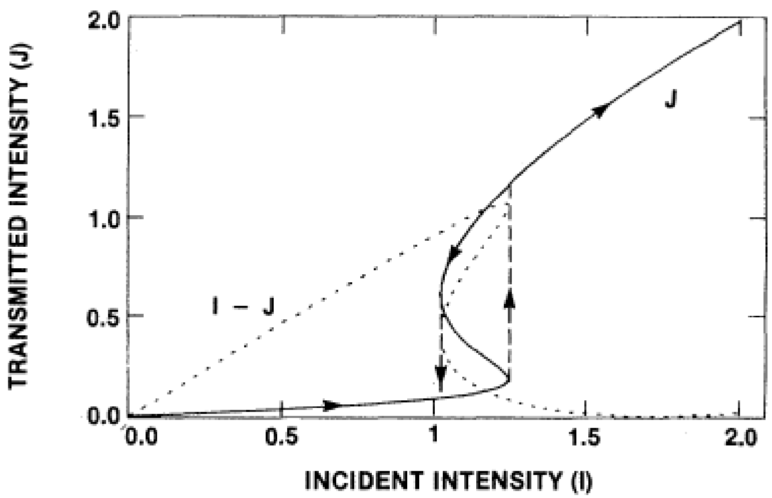
VOLUME 49, NUMBER 16 PHYSICAL REVIEW LETTERS 18 OCTOBER 1982

Nonlinear Reflection in Cholesteric Liquid Crystals: Mirrorless Optical Bistability

Herbert G. Winful
Advance Technology Laboratory, GTE Laboratories, Inc., Waltham, Massachusetts 02254
(Received 27 April 1982)







Intense light changes period of cholesteric helix, thereby tuning stop and resulting in bistability

Time-dependent Nonlinear Coupled-Mode Equations

Impossible d'afficher l'image. Votre ordinateur manque peut-être de mémoire pour ouvrir l'image ou l'image est endommagée. Redémarrez l'ordinateur, puis ouvrez à nouveau le fichier. Si le x rouge est toujours affiché, vous devrez peut-être supprimer l'image avant de la réinsérer.

H. Winful, Appl. Phys. Lett. (1981)

$$\frac{\partial E_F}{\partial z} + \frac{n_0}{c}\frac{\partial E_F}{\partial t} = i\kappa E_B e^{-i2\Delta\beta z} + i\gamma\left(\left|E_F\right|^2 + 2\left|E_B\right|^2\right)E_F$$

$$\frac{\partial E_B}{\partial z} - \frac{n_0}{c}\frac{\partial E_B}{\partial t} = -i\kappa E_F e^{+i2\Delta\beta z} - i\gamma\left(\left|E_B\right|^2 + 2\left|E_F\right|^2\right)E_B$$

Predict self-pulsing, modulational instability, pulse compression, propagating solitons (Winful, 1981, 1985)
Also, slow Bragg solitons (Christodoulides and Joseph, 1989)

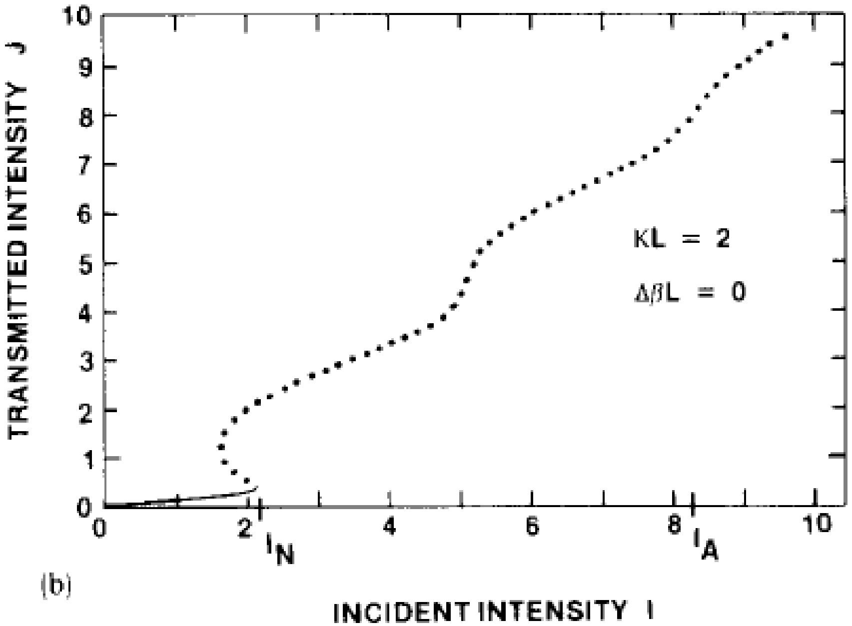
Self-pulsing and chaos in distributed feedback bistable optical devices

Herbert G. Winful and Gene D. Cooperman
Advance Technology Laboratory, GTE Laboratories Incorporated, 40 Sylvan Road, Waltham, Massachusetts 02254

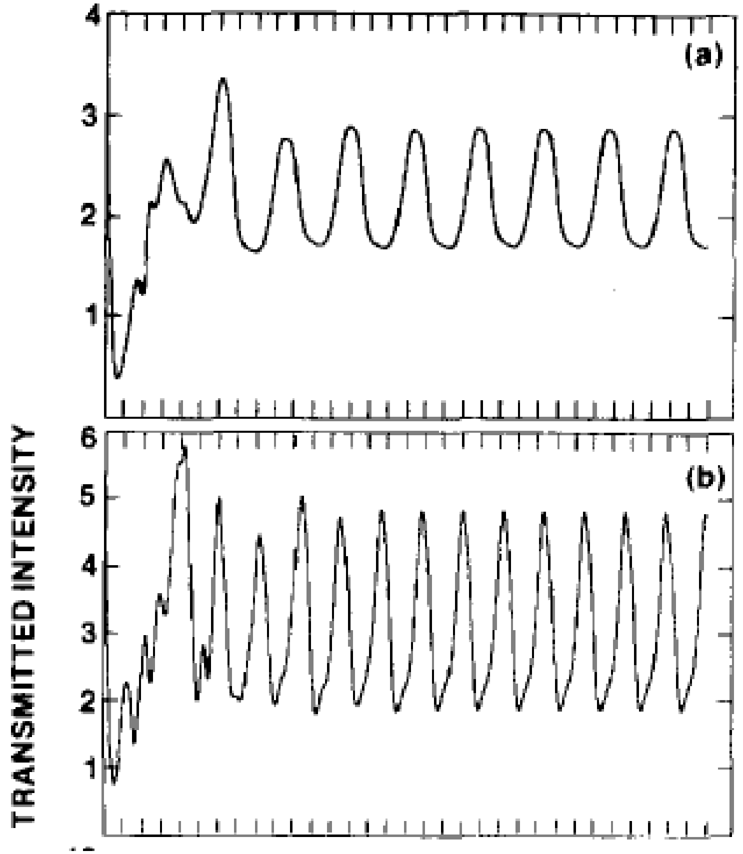
(Received 28 September 1981; accepted for publication 19 November 1981)

We show that the light transmitted by a nonlinear distributed feedback structure can be steady (time independent), periodic, or chaotic depending on the intensity of the input cw beam. The feasibility of an experimental demonstration of such behavior is discussed.

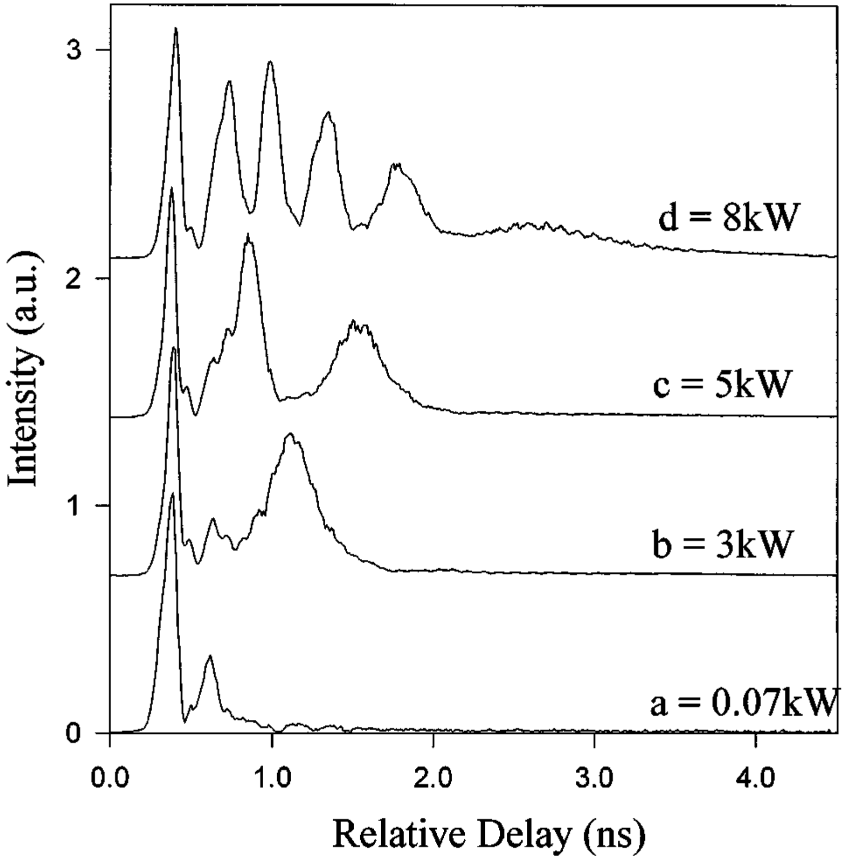
Prediction of self-pulsing and chaos in nonlinear periodic structures (Appl. Phys. Lett. 40, 298, 1981)



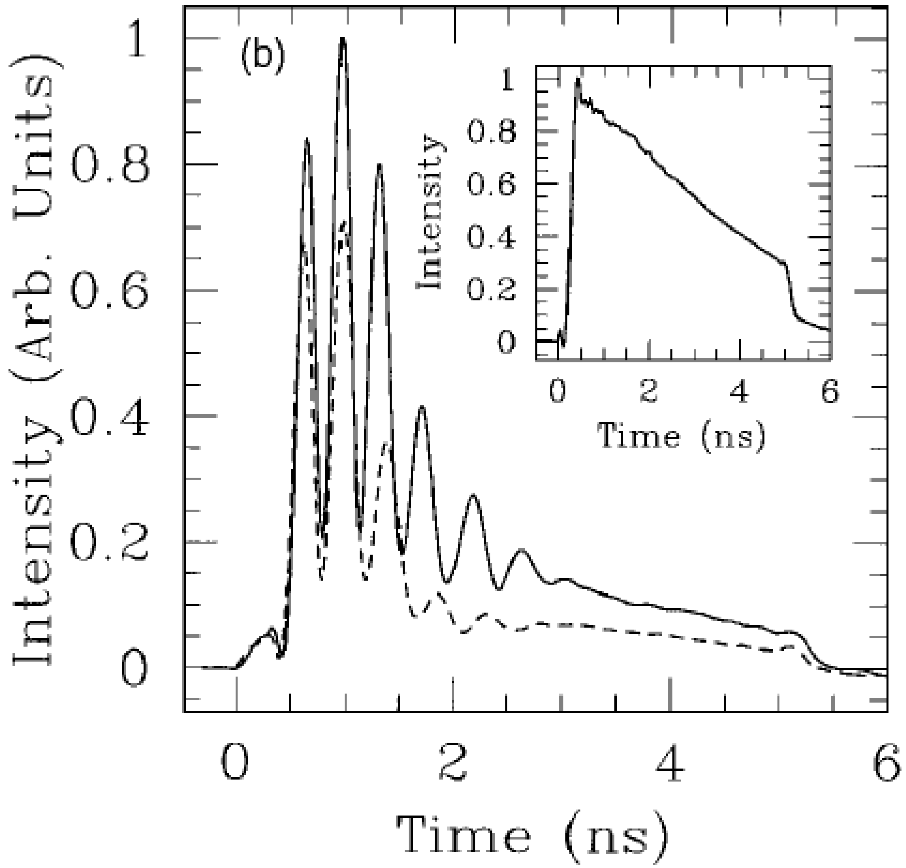
(b)



Observation of self-pulsing



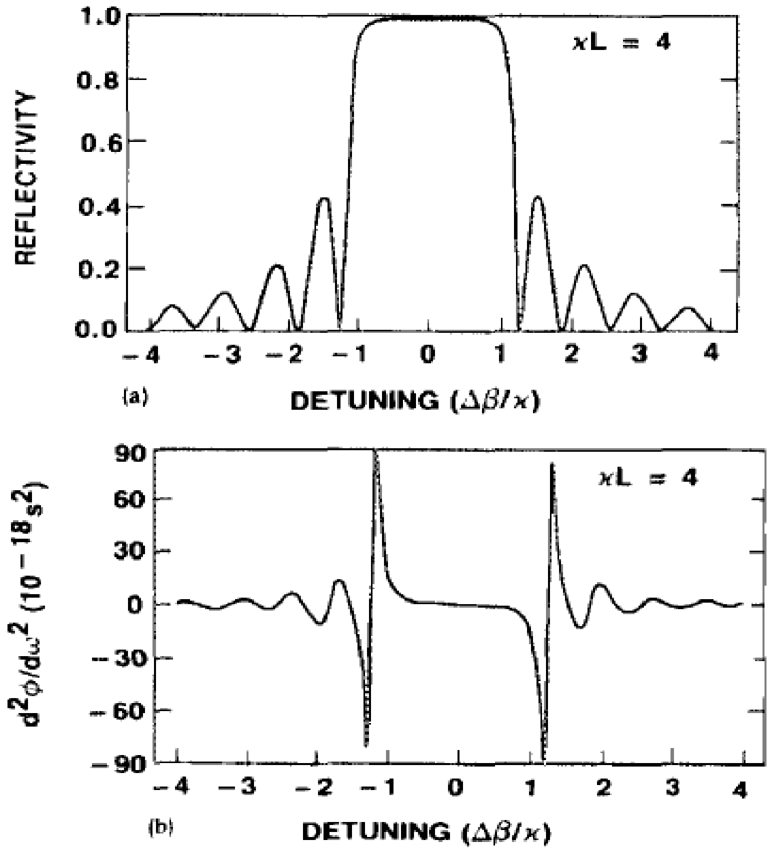
Taverner, et al, Opt. Lett. 23, 328 (1998)



Broderick, et al, Opt. Lett. 25, 536 (2000)

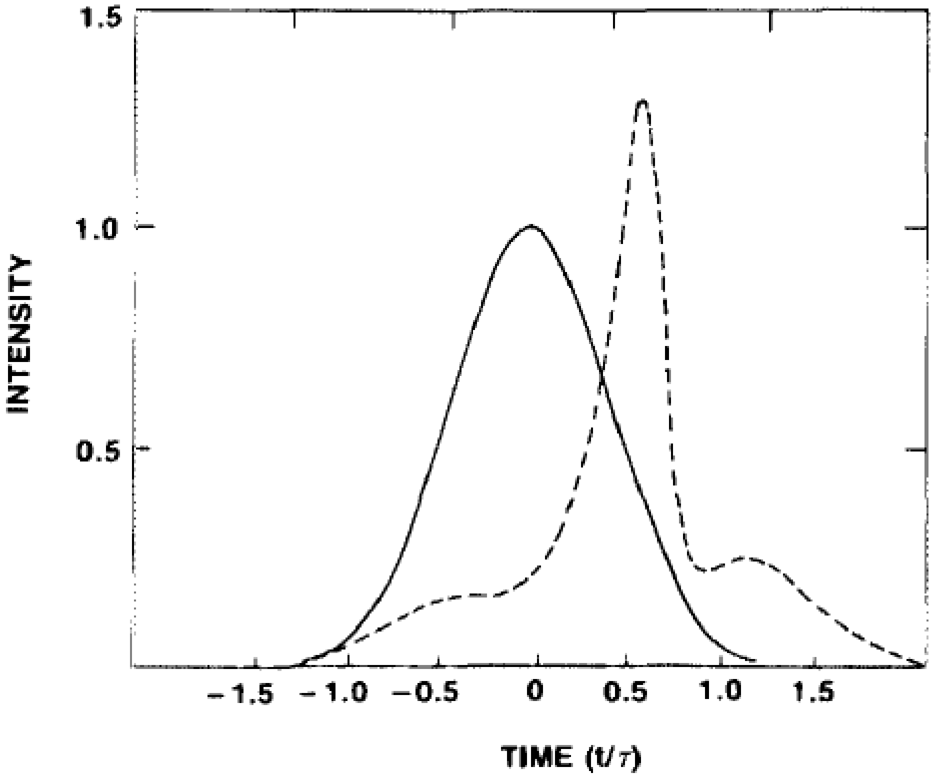
Pulse compression in nonlinear periodic structures

- Periodic structures provide large values of both positive and negative GVD
- Proposal: the self-phase modulation and negative GVD in a periodic structure should enable pulse compression and soliton propagation (Winful, APL, 46, 527, 1985)

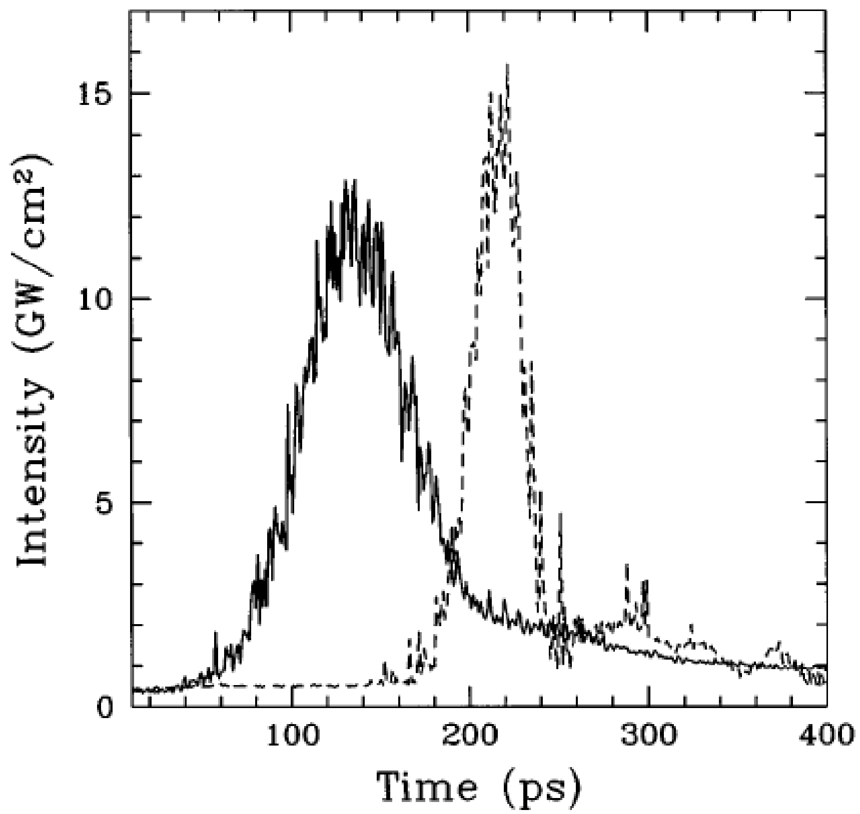


Pulse compression

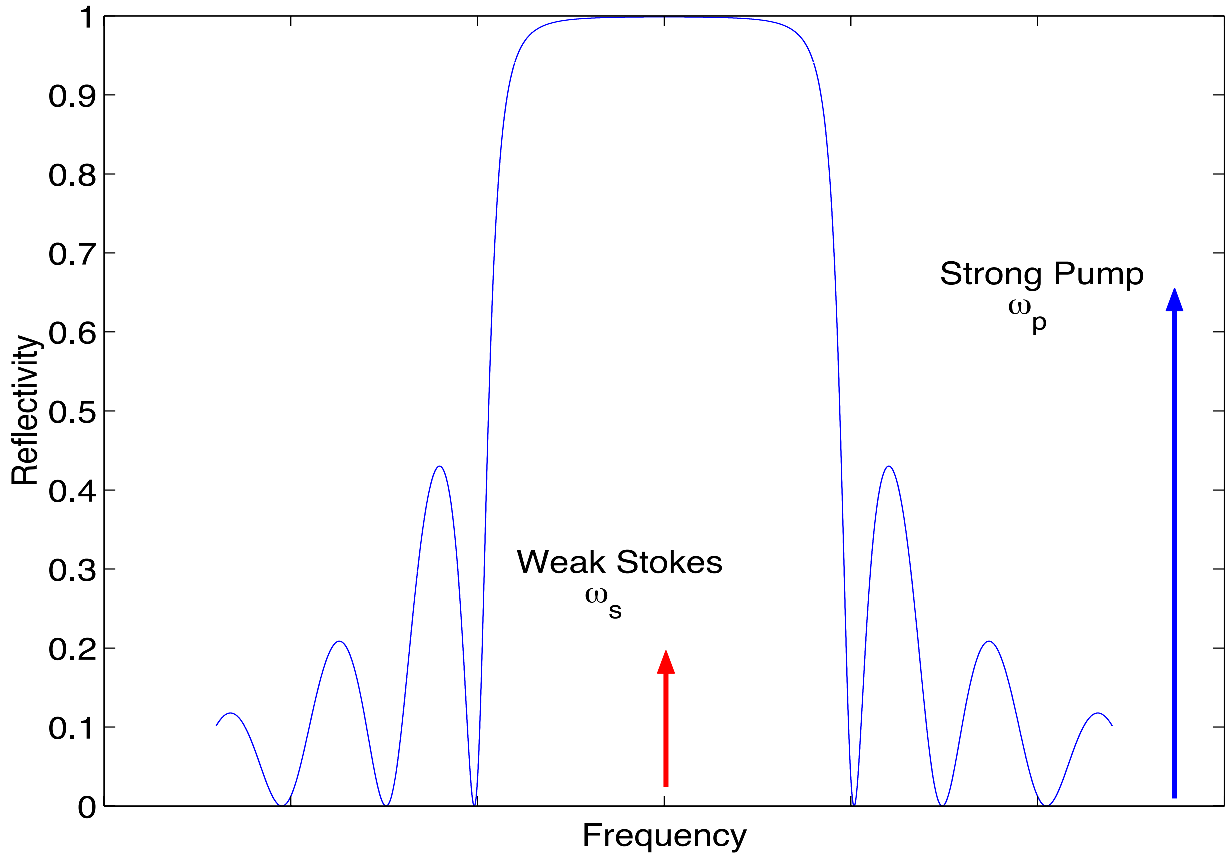
Theory (Winful, 1985)



Expt. (Eggleton, et al, 1996)

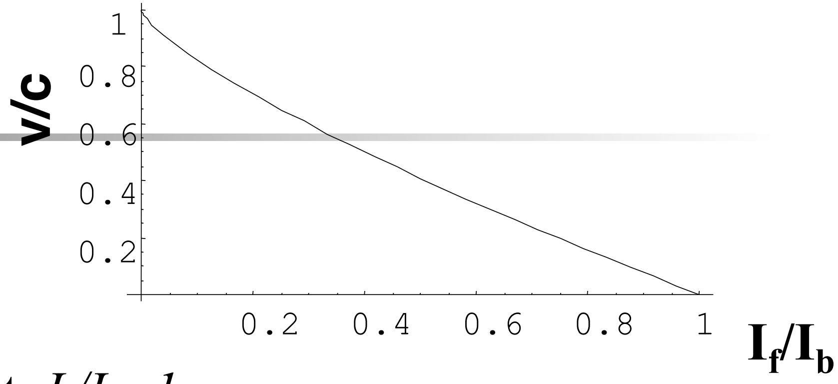


Stimulated Raman Scattering in Periodic Structures



H. G. Winful and V. E. Perlin, Phys. Rev. Lett. **84**, 3586 (2000)

Raman gap solitons: main idea



Gap solitons – solutions of NLCME with envelope **$\mathrm{sech}^2(t-z/v)$** (spectrum within the bandgap)

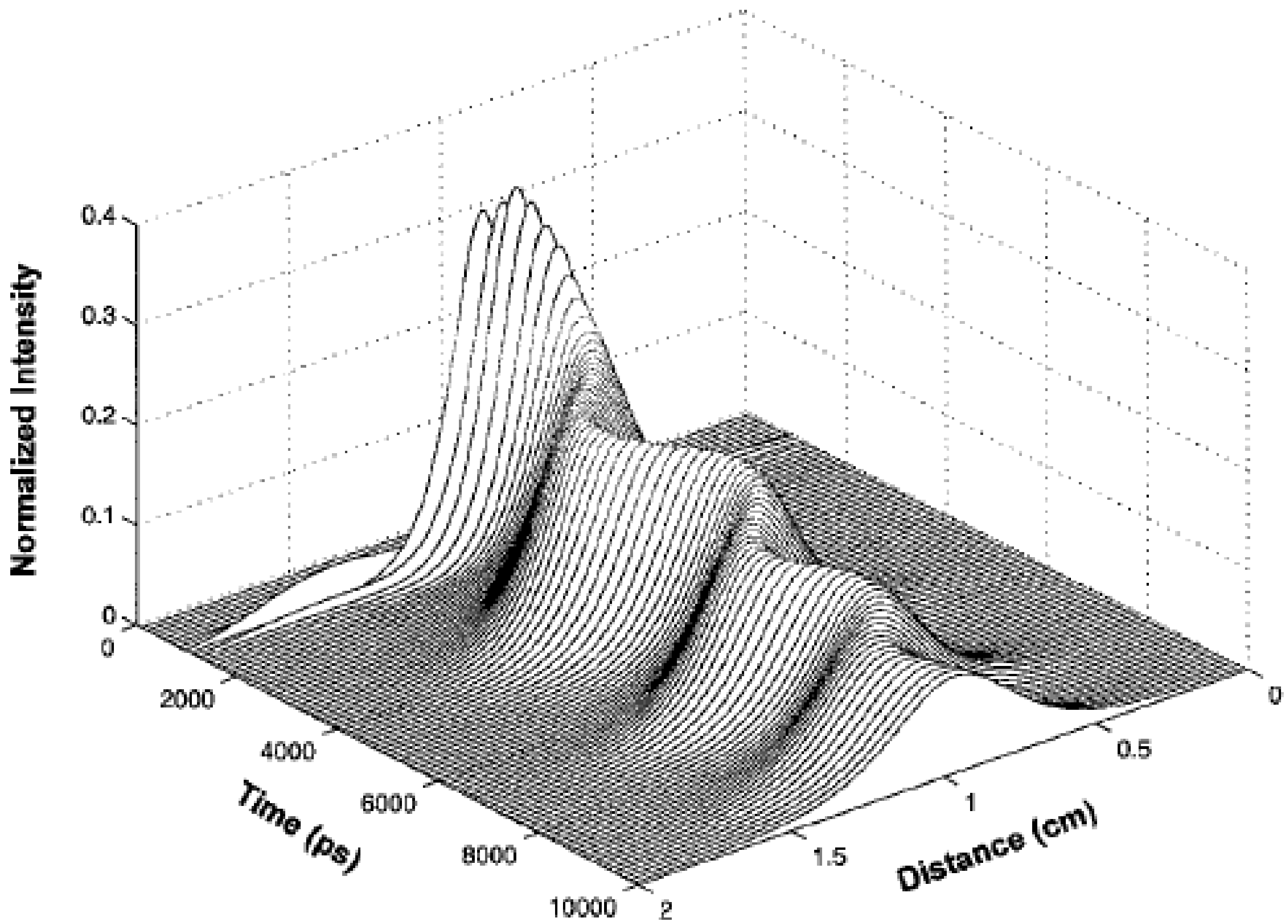
Need: signal inside the grating, such that $I_f/I_b \sim 1$

Cannot: just use strong signal, that switches itself, since then $I_f >> I_b$

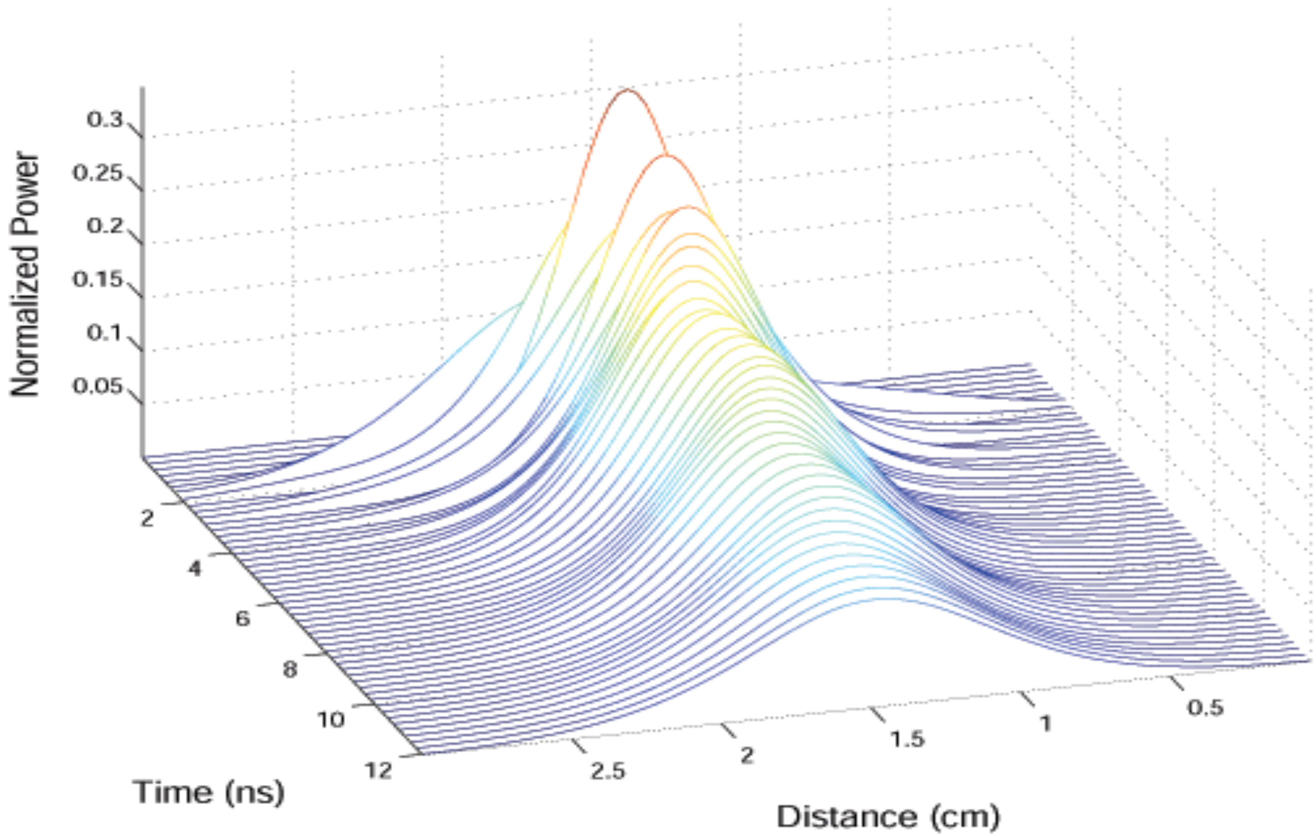
Try: 1. Weak cw signal at the frequency in the bandgap

2. Intense pump pulse detunes the grating and allows the signal in
3. Signal gets amplified by SRS inside the grating
4. Forward and backward components are amplified equally
5. Pump pulse is gone
6. Signal is trapped in the grating and it evolves into a gap soliton

Slow Raman gap soliton

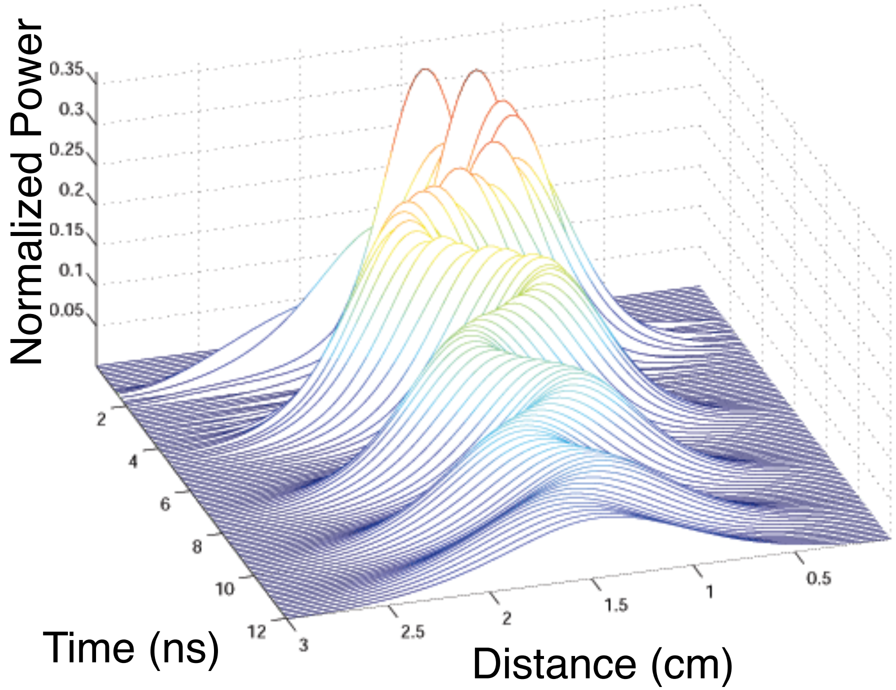


Stationary Raman gap soliton

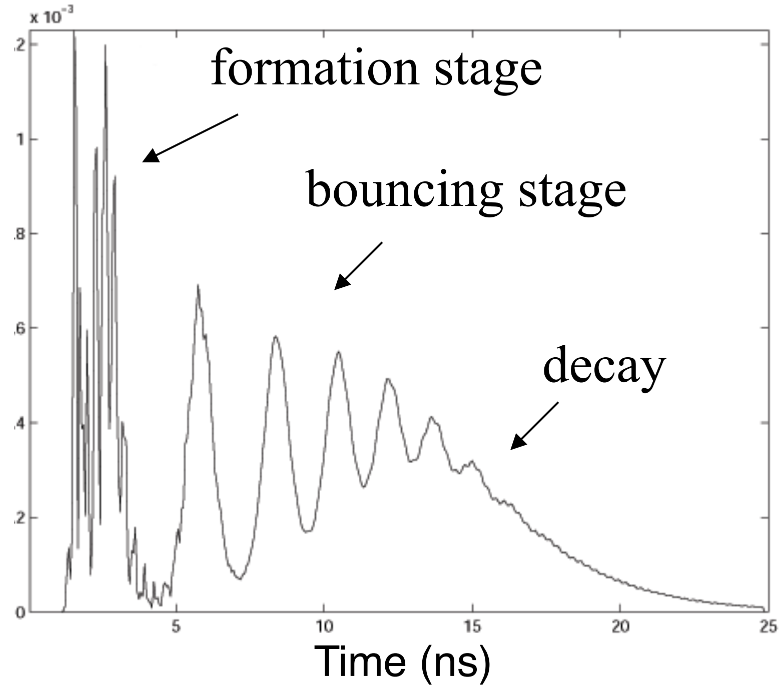


H. G. Winful and V. E. Perlin, Phys. Rev. Lett. **84**, 3586 (2000)

Slow Raman gap solitons

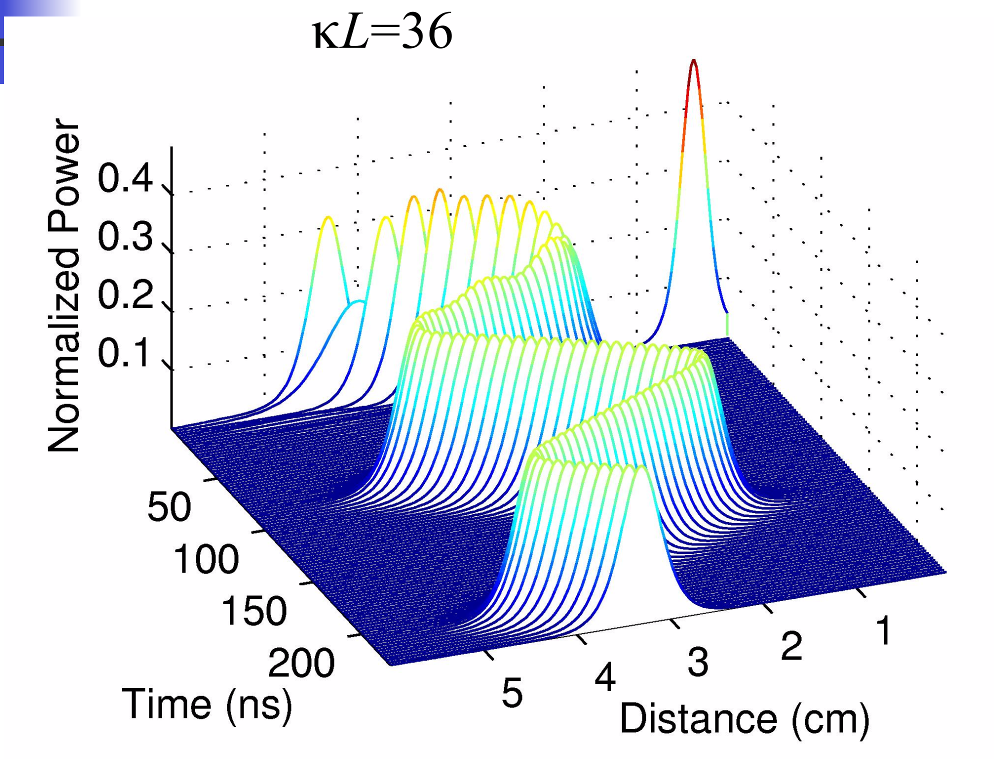


Output trace:



- Stay in the grating long after the pump is gone
- Fit the gap soliton solution (for infinite periodic structure)
- Pulse width inversely proportional to intensity

Long-lifetime Raman gap solitons



$$\frac{v}{c} \approx 0.001$$

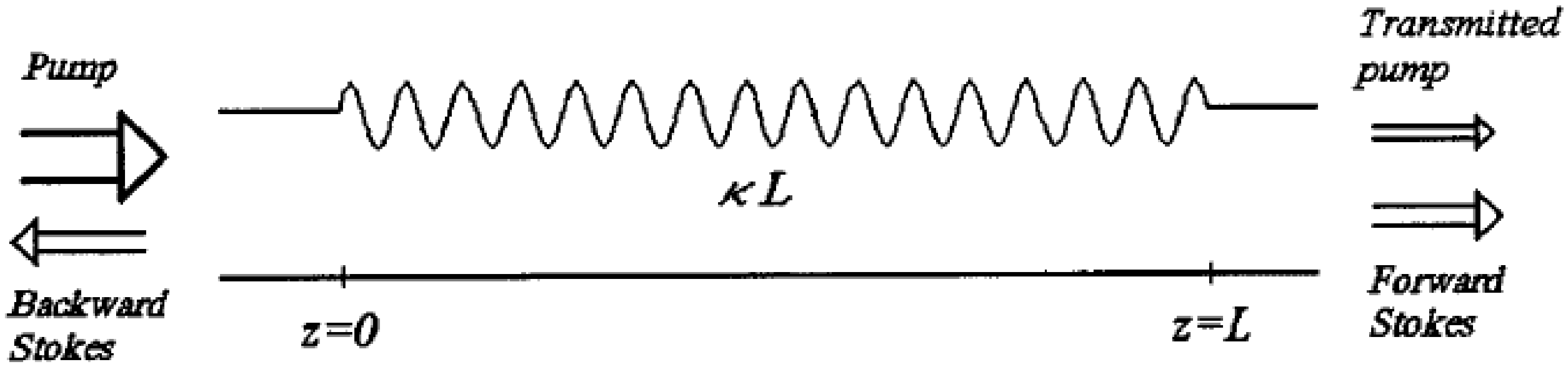
- Scaling: $\tau \sim 1/I$, $I \sim \kappa$, $\tau/L \sim 1/\kappa L$, need stronger gratings
- Gap soliton lifetime in finite structure $\sim 1/v^2$

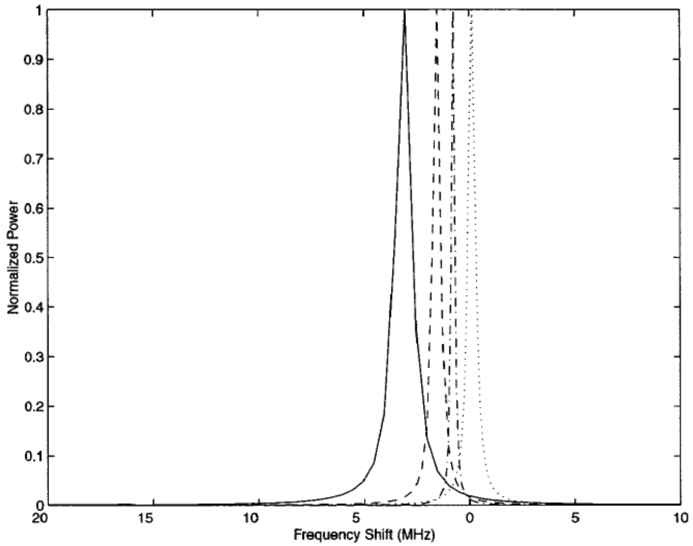
Propagation velocity does not change upon reflections !

IEEE JOURNAL OF QUANTUM ELECTRONICS, VOL. 37, NO. 1, JANUARY 2001

Distributed Feedback Fiber Raman Laser

Victor E. Perlin and Herbert G. Winful





Should enable Raman lasers with very narrow linewidth

August 1, 2011 / Vol. 36, No. 15 / OPTICS LETTERS 2895

Raman fiber distributed feedback lasers

Paul S. Westbrook,* Kazi S. Abedin, Jeffrey W. Nicholson,
Tristan Kremp, and Jerome Porque
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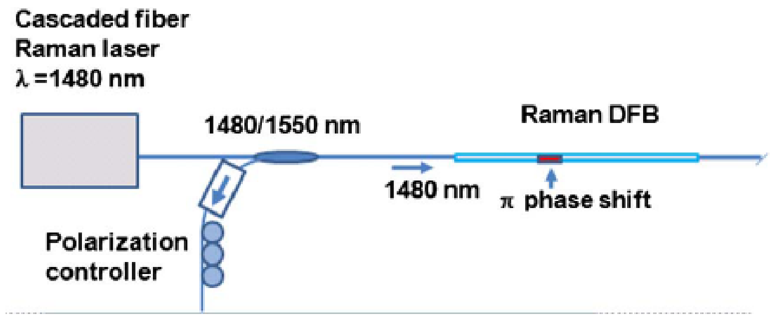
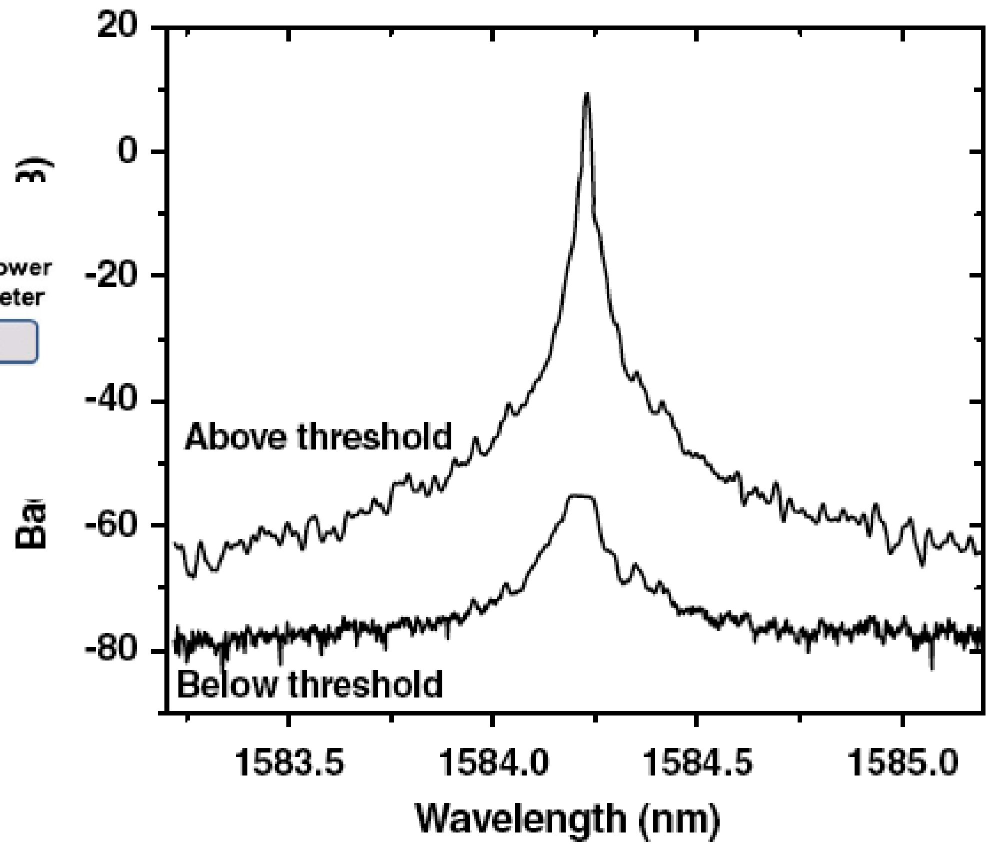
**Corresponding author: westbrook@ofsoptics.com*





Output power: 350mW
Linewidth: 4MHz
Threshold pump: 4.3W

Conclusions

- Nonlinear periodic structures make possible a large number of phenomena including bistability, self-pulsing, pulse compression, gap solitons, and DFB Raman lasing.

VOLUME 7, NUMBER 4 PHYSICAL REVIEW LETTERS AUGUST 15, 1961

GENERATION OF OPTICAL HARMONICS*

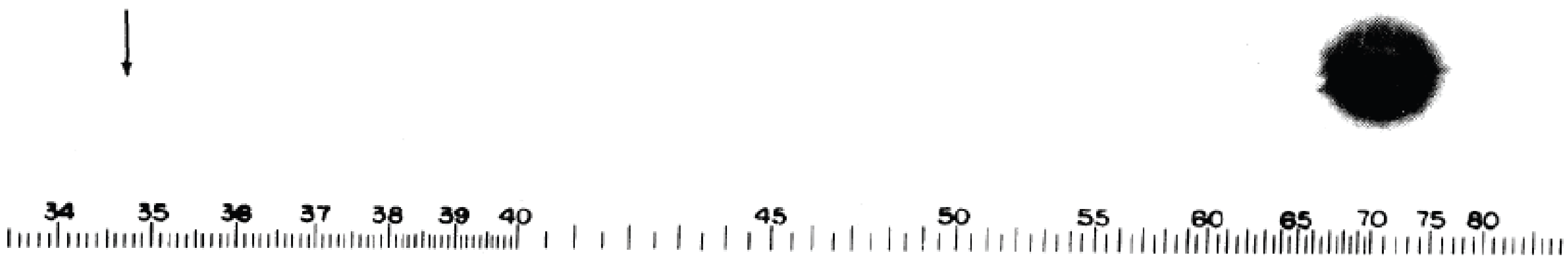
P. A. Franken, A. E. Hill, C. W. Peters, and G. Weinreich
The Harrison M. Randall Laboratory of Physics, The University of Michigan, Ann Arbor, Michigan

NONLINEAR OPTICS AT 50

A SYMPOSIUM AT THE UNIVERSITY OF MICHIGAN CELEBRATING THE 50th ANNIVERSARY OF THE BIRTH OF NONLINEAR OPTICS

Wednesday, October 26, 2011

http://nlosymposium.physics.lsa.umich.edu/

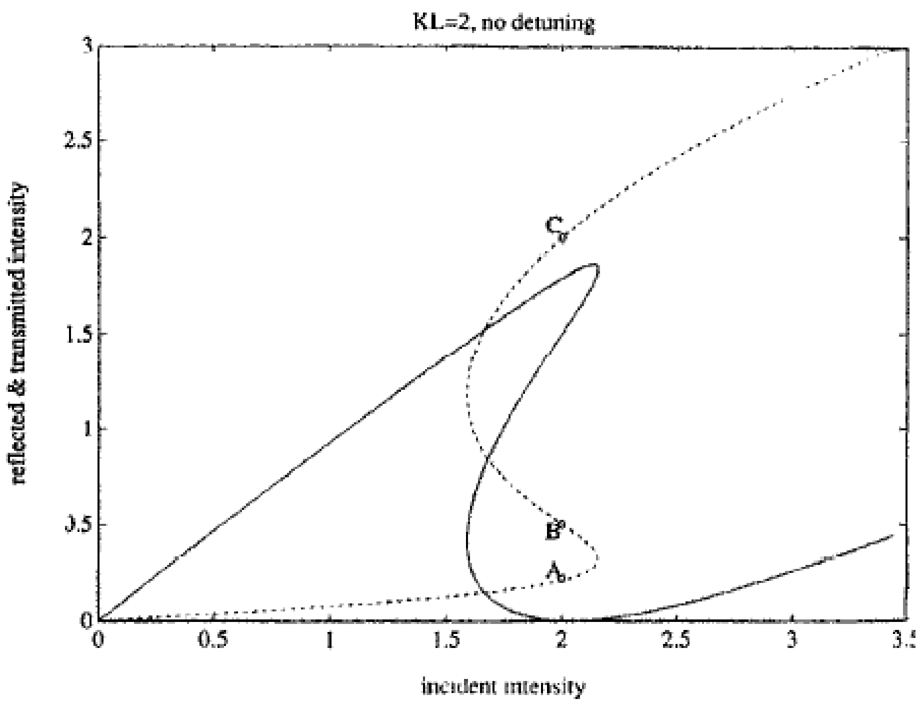


Jack Marburger
(February 8, 1941 – July 28, 2011)

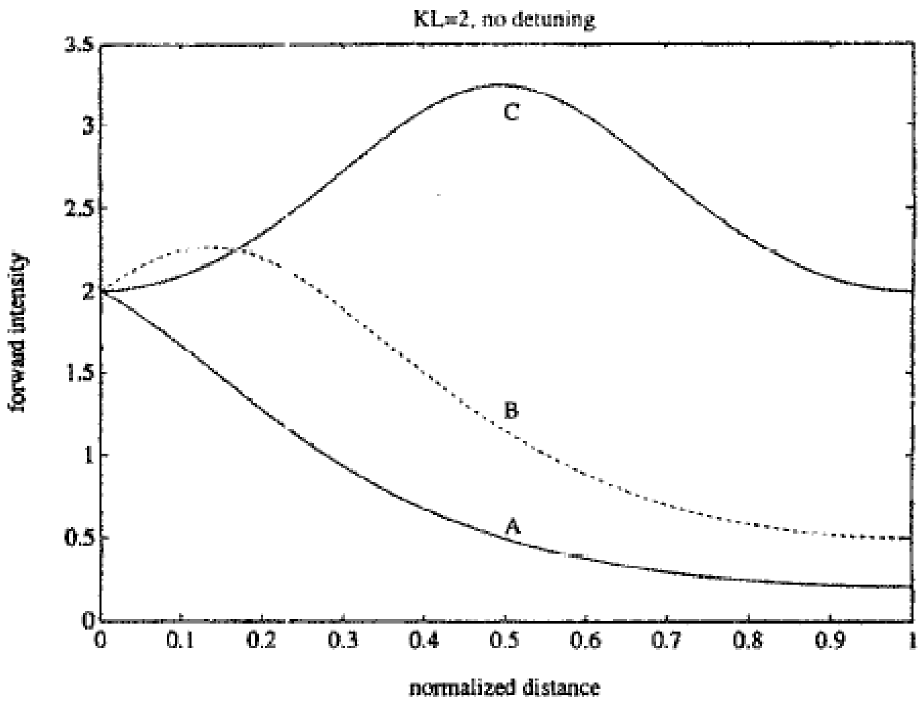
Steady state solutions

$$y(\zeta) = \frac{J}{1 + [y_{-} / y_{+}] sn^2[(\zeta - 1) y_{+} \mid (y_{-} / y_{+})^2]}$$

Gap soliton

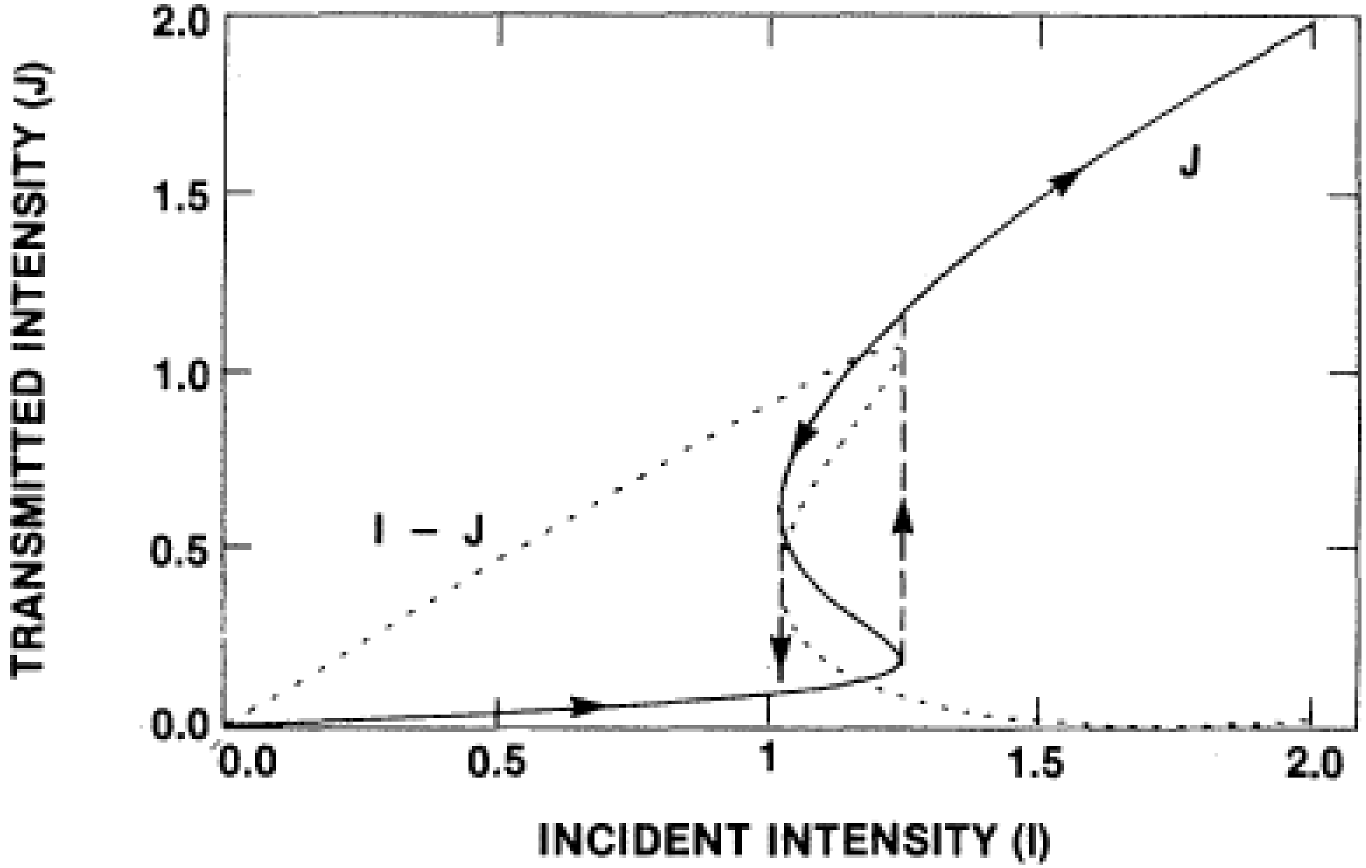


KL=2, no detuning
reflected & transmitted intensity
incident intensity
C
B
A
0
0.5
1
1.5
2
2.5
3
3.5



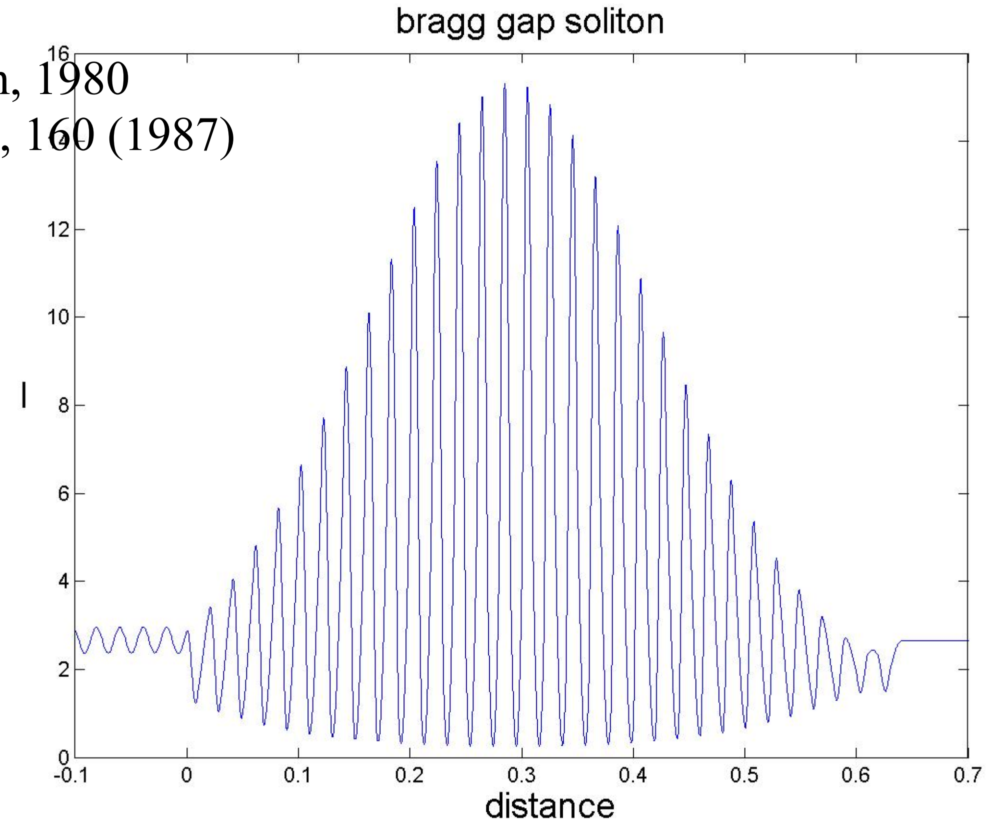
KL=2, no detuning
forward intensity
normalized distance
C
B
A
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
1.5
2
2.5
3
3.5

Bistability in cholesteric liquid crystal

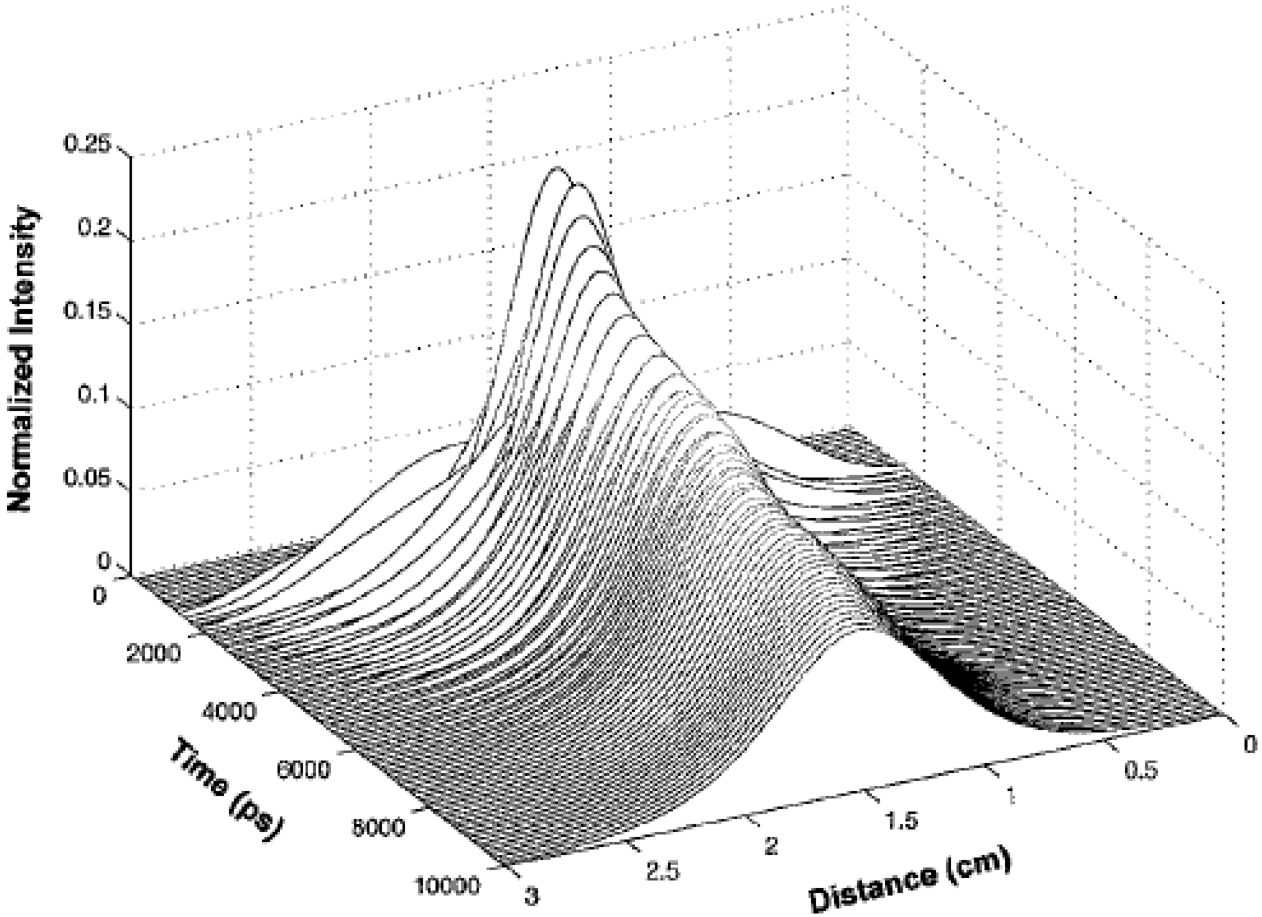


Gap soliton

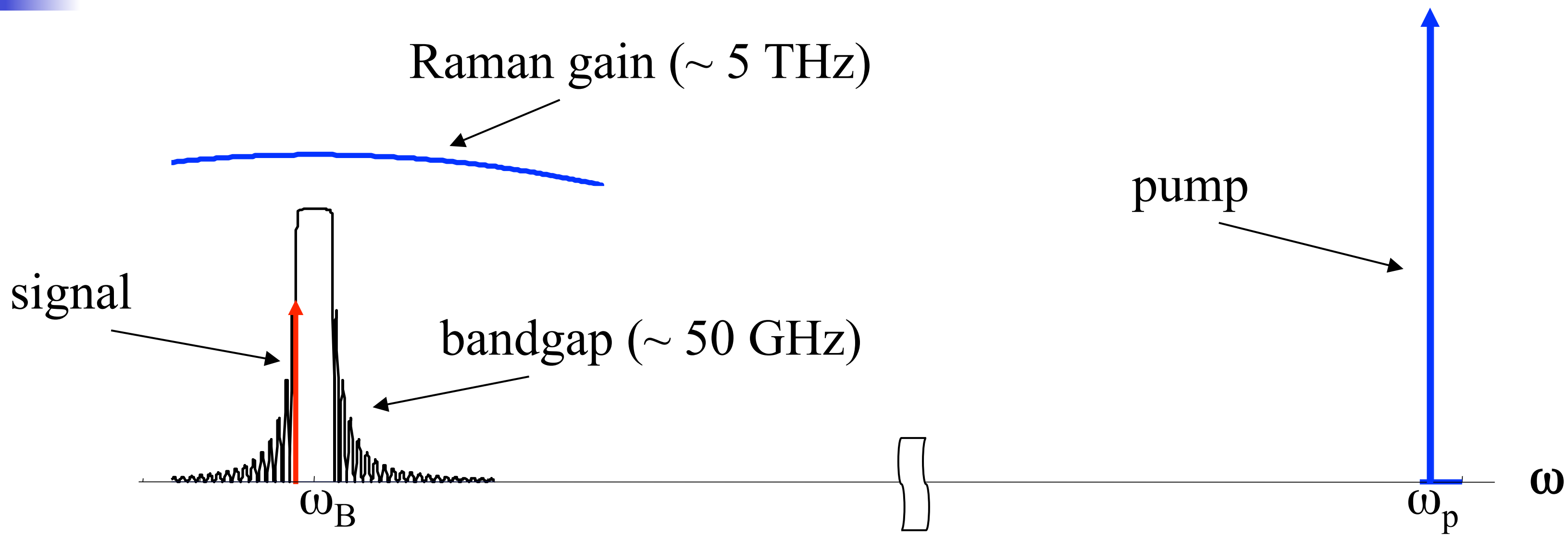
Winful, PhD dissertation, 1980
Chen and Mills, PRL 58, 160 (1987)



Raman Gap Soliton

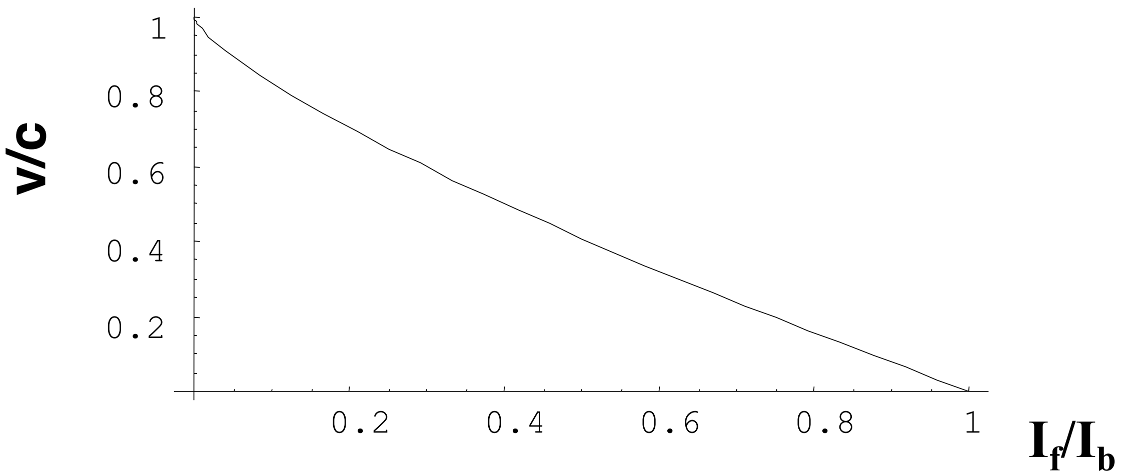


… in frequency domain

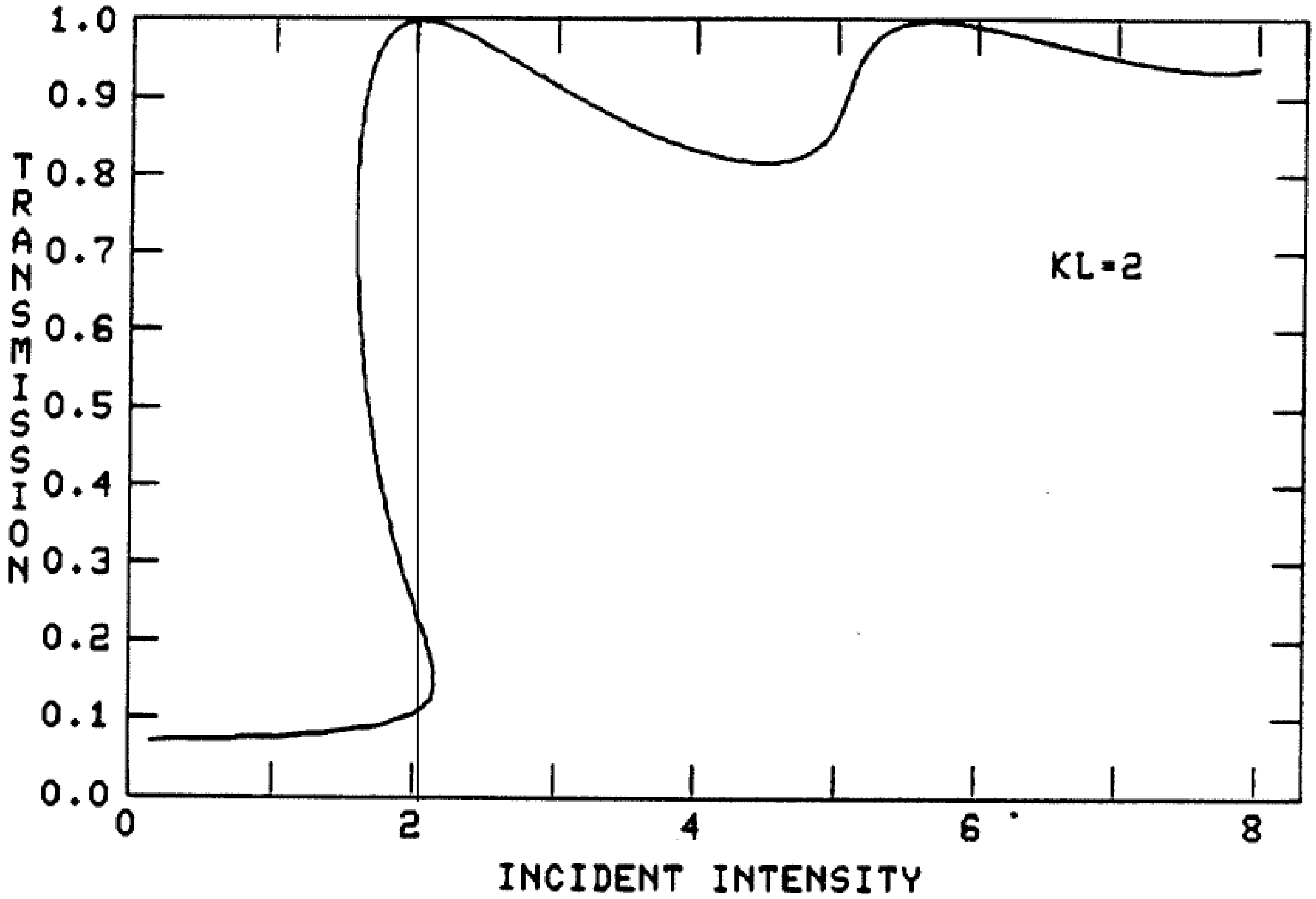


- Raman gain spectrum is much broader than the bandgap
- Pump does not interact with periodic structure, just gain and XPM
- All frequencies around bandgap experience the same gain

- To date, the stationary gap soliton has not been observed



Nonlinear Transmission



Transmission