Nano-Structure Modeling for Optical Interconnect Applications

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We are numerically solving (finite differences) in the time domain, the full-wave, vector Maxwell's equations with linear and nonlinear materials models:

multi-dimensional NL-FDTD method

ECE EM Lab

- Can model arbitrary source fields; e.g., Gaussian beams with specified waists and incidence angles
- Can model transverse power flows, nonlinear couplings, back reflections, and polarization effects
- Can include detailed material models:
  nonresonant (phenomonological) or
  resonant (two-level) effects
- Can model realistic devices and systems
  - complex structures and their couplings
- Can model single cycle or multiple cycle pulses to establish differences in their behaviors

The NL-FDTD method is very versatile

The electromagnetic field properties of the basic VCSEL structure were studied

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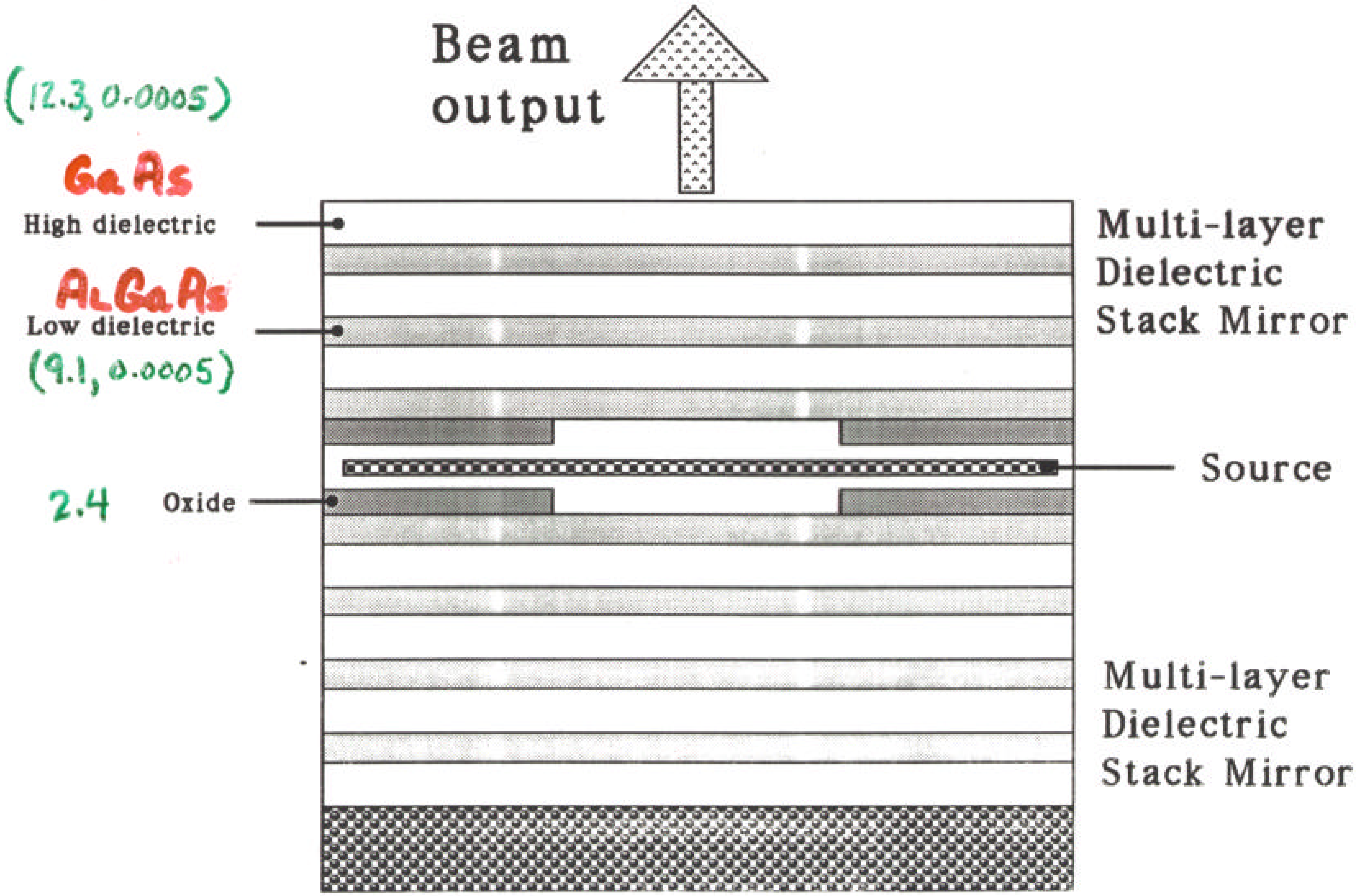

We are numerically solving in a self-consistent manner the full-wave vector Maxwell's equations and several materials models

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Maxwell's Eqns:

$$\nabla \times \vec{E} = -\mu_0 \partial_t \vec{H}$$

$$\nabla \times \vec{H} = \epsilon_0 \partial_t \vec{E} + \partial_t \vec{P}_{TOTAL}$$

$$\vec{P}_{TOTAL} = \vec{P}_L + \vec{P}_{NL}$$

Linear Dispersion (Lorentz) Model:

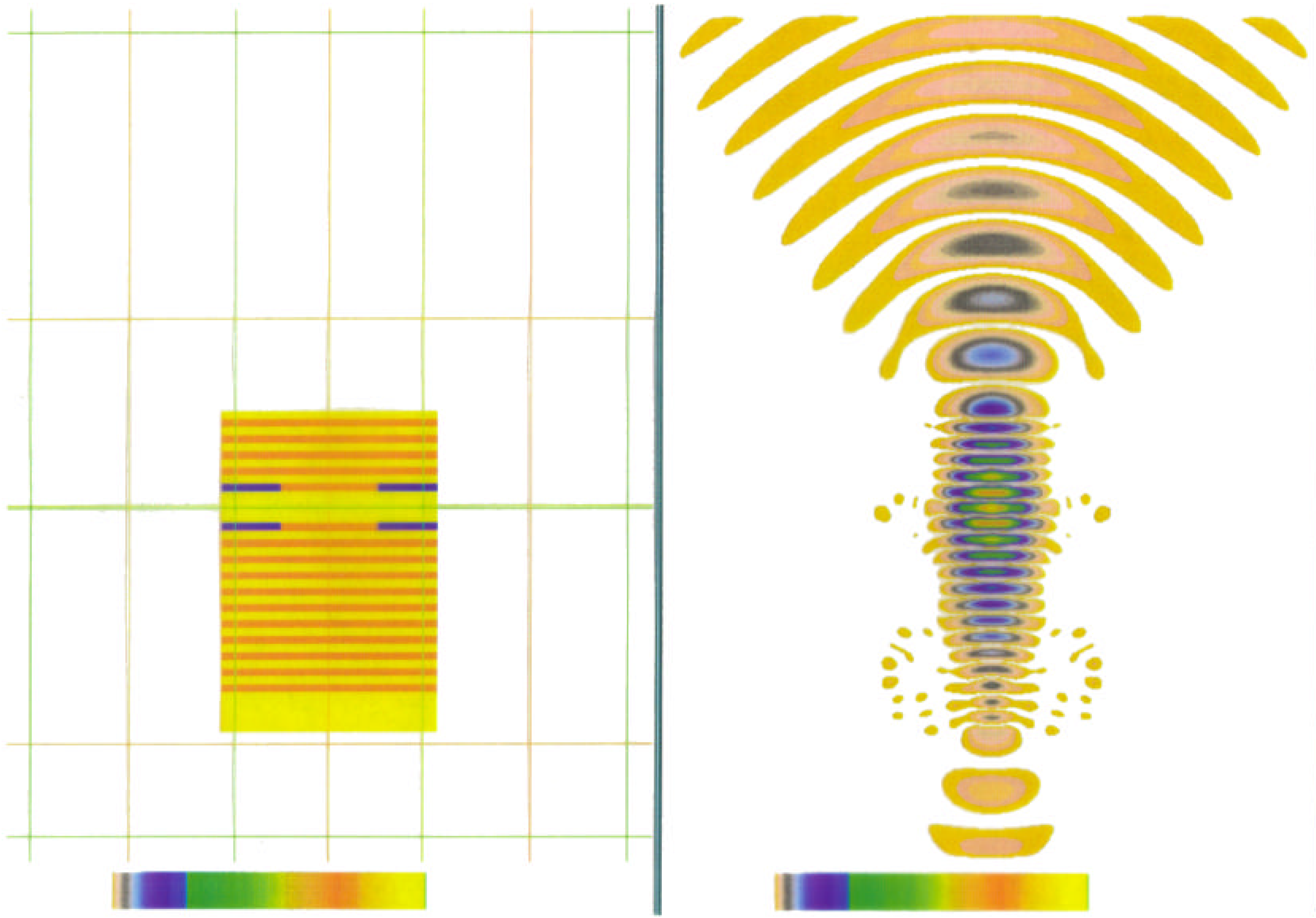
$$\partial_t^2 \vec{P}_L + \Gamma_L \partial_t \vec{P}_L + \omega_L^2 \vec{P}_L = \epsilon_0 \chi_0 \omega_L^2 \vec{E}$$

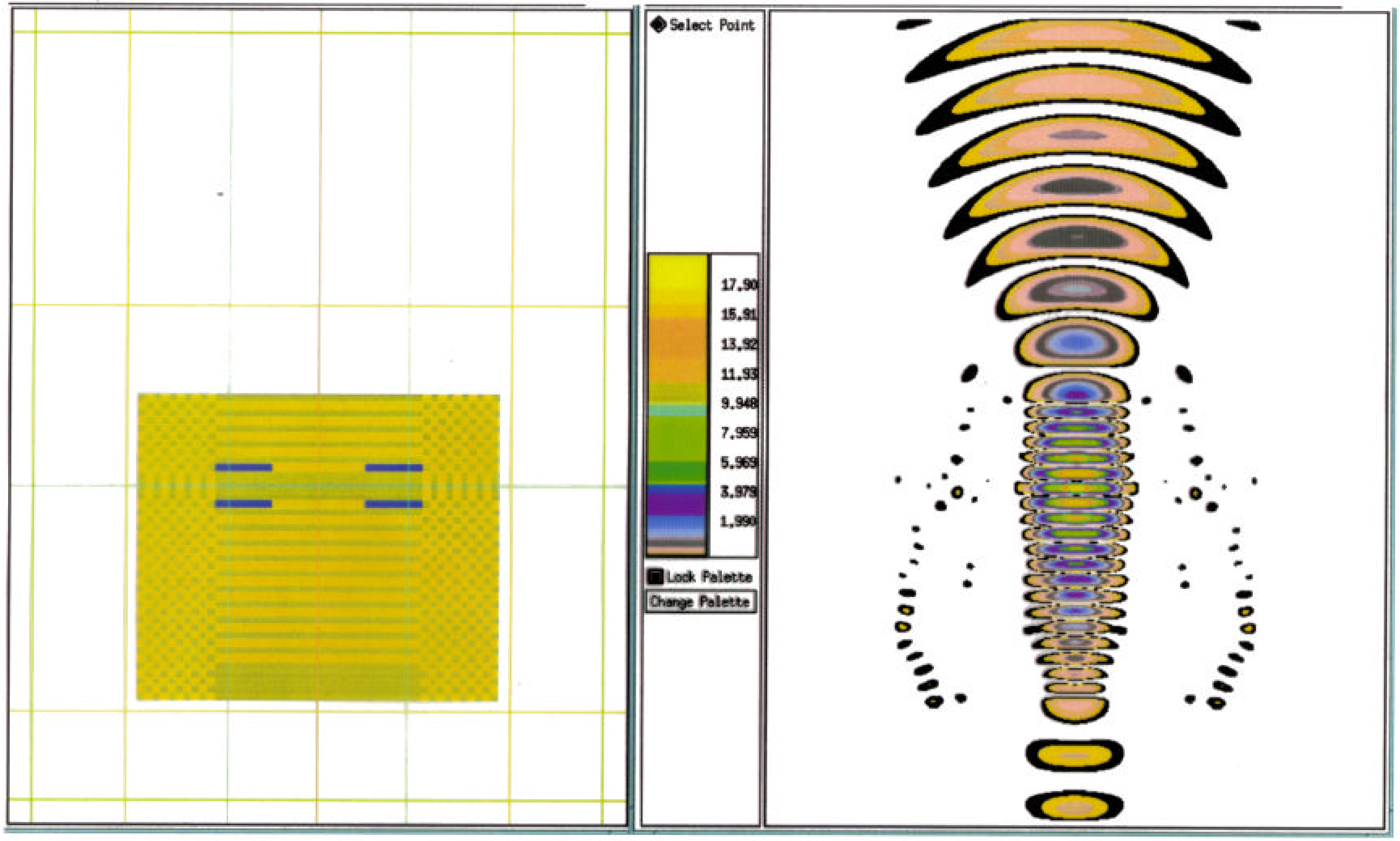
Nonlinear Raman Model:

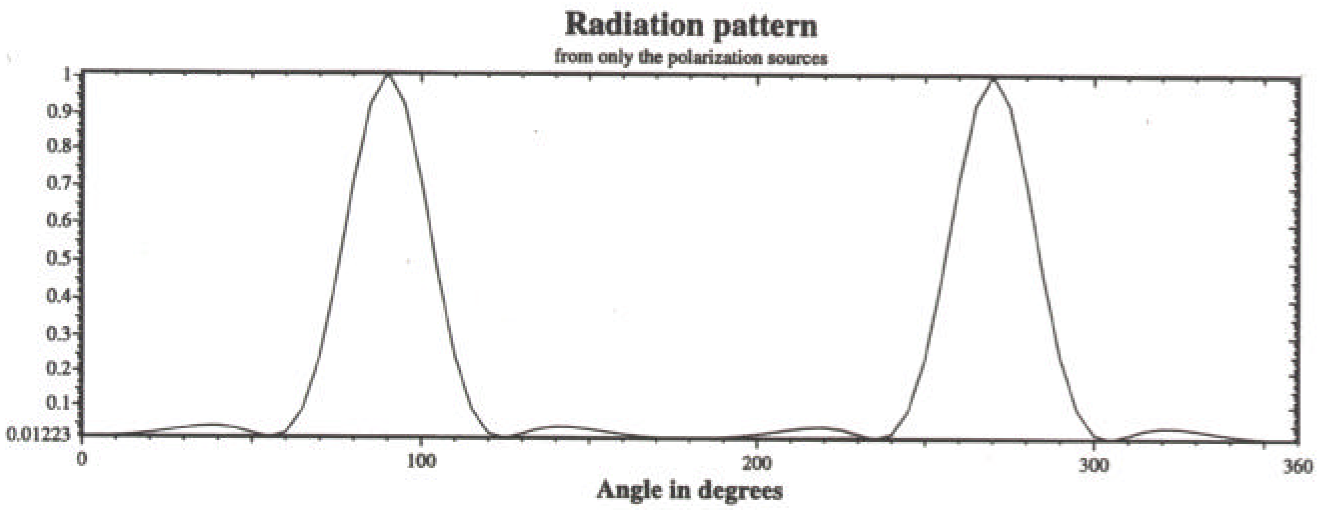
$$\vec{P}_{NL} = \epsilon_0 \chi_{NL} \vec{E} + \epsilon_0 \chi_{KERR} |\vec{E}|^2 \vec{E}$$

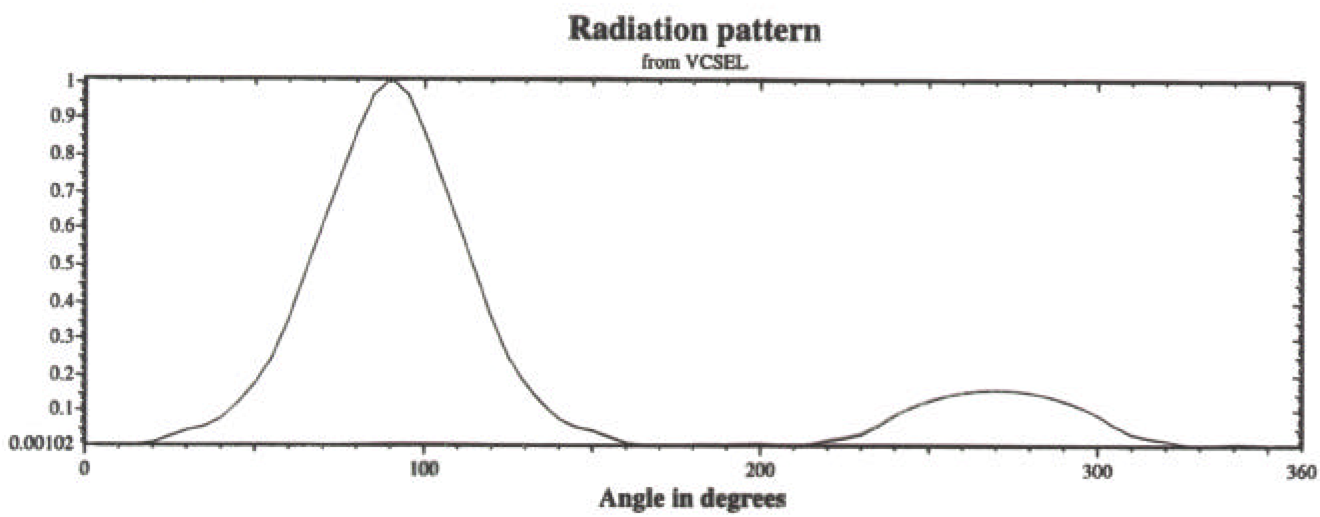
$$\partial_t^2 \chi_{NL} + \omega_R^2 \left(\tau_R \partial_t \chi_{NL} + \chi_{NL} \right) = \epsilon_2 \omega_R^2 |\vec{E}|^2$$

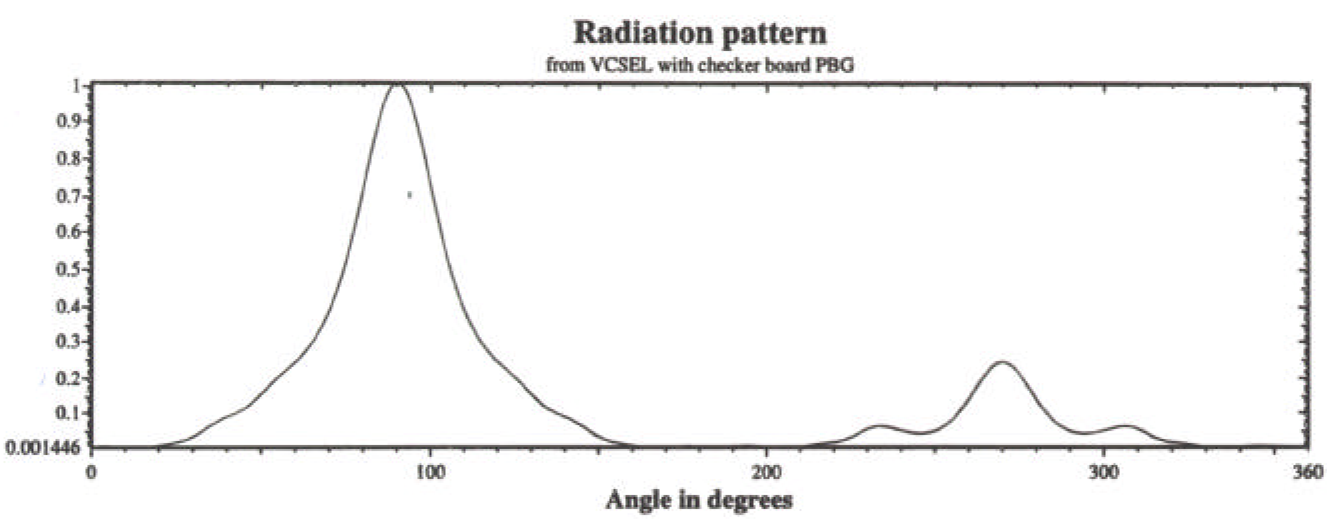
Multi-dimensional NL-FDTD Method

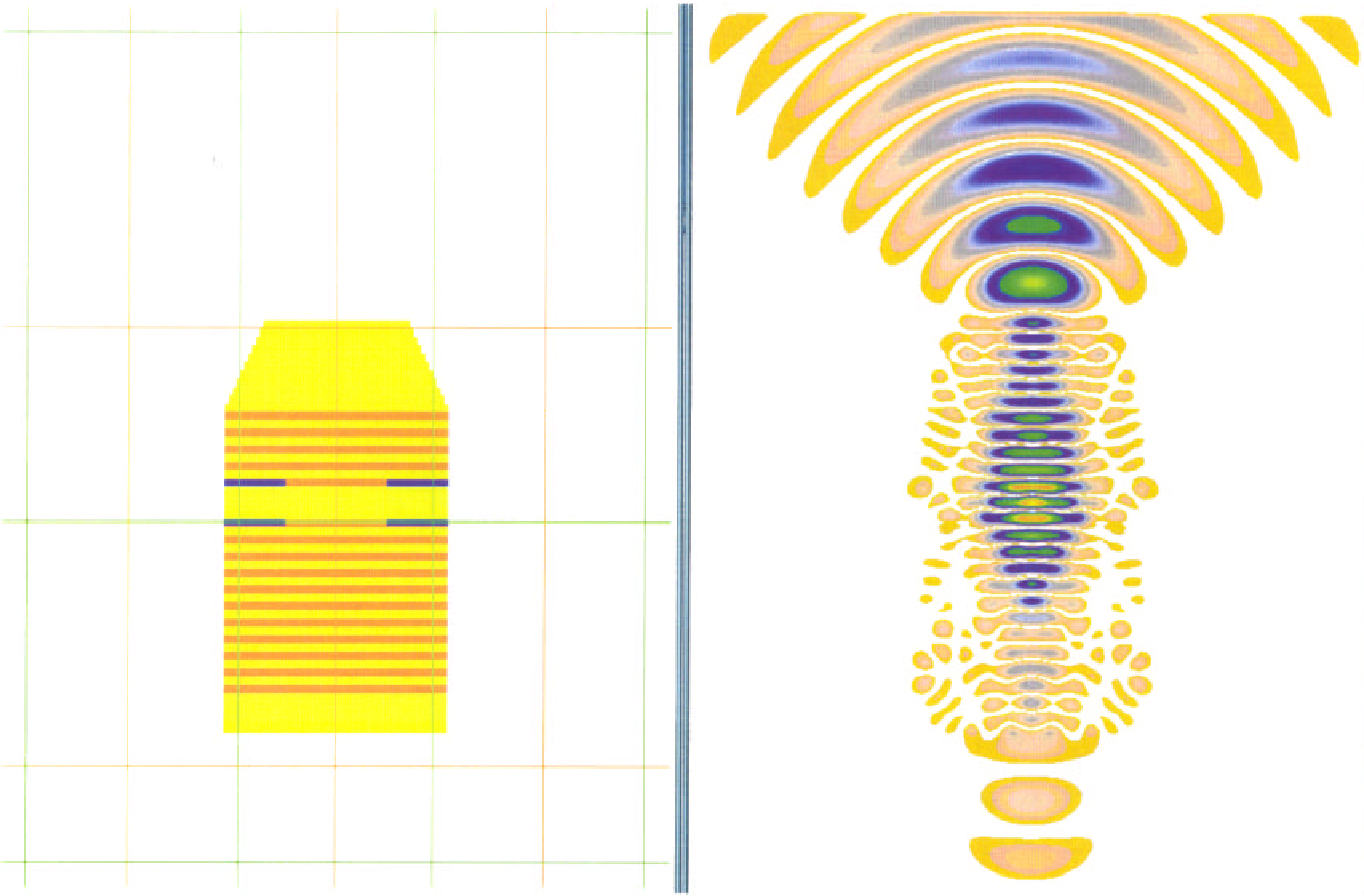


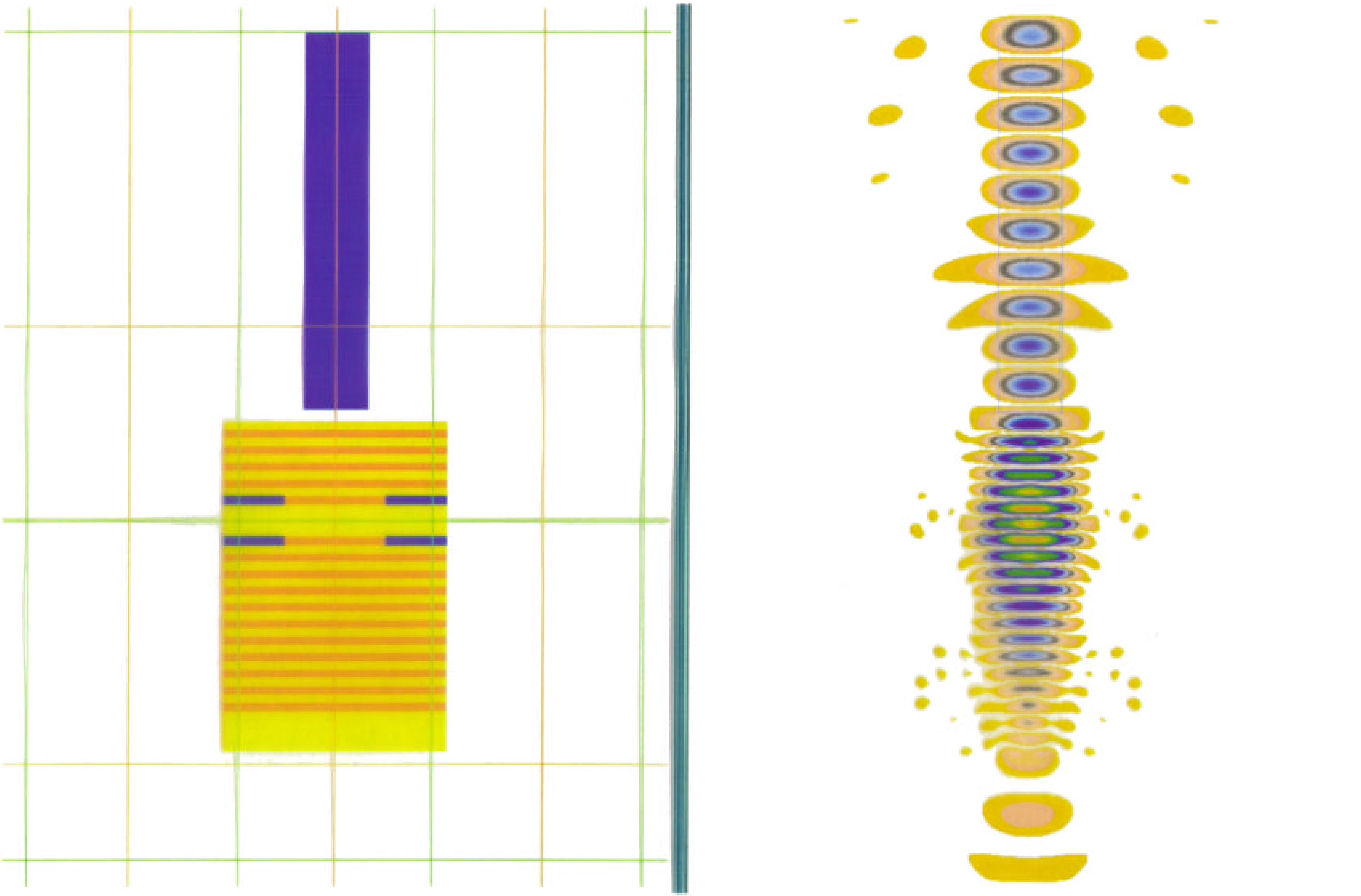

Select Point
17.90
15.91
13.92
11.93
9.948
7.959
5.969
3.979
1.990
Lock Palette
Change Palette

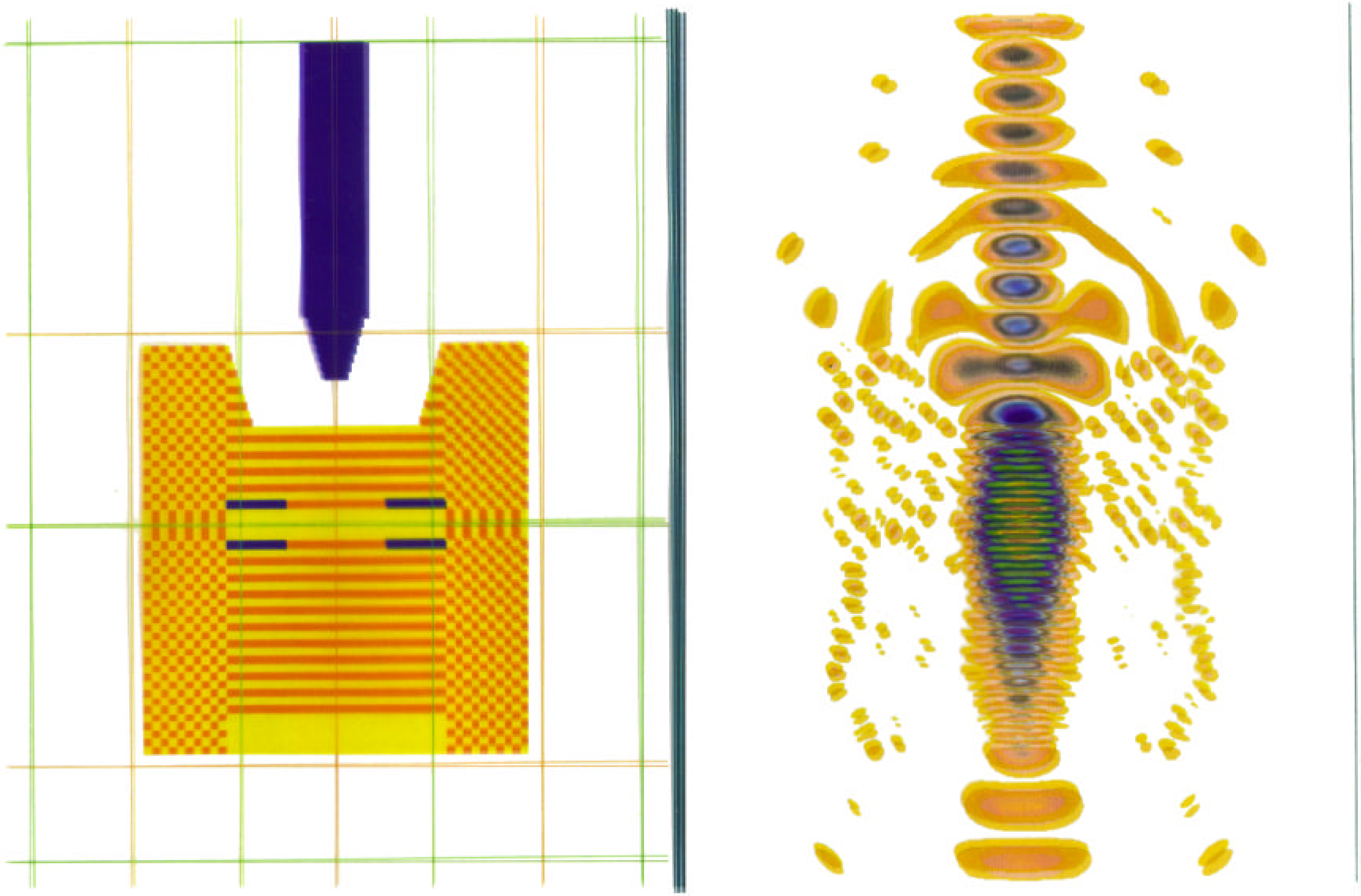

Radiation pattern
from only the polarization sources
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.01223
0
100
200
300
360
Angle in degrees


Radiation pattern
from VCSEL
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.00102
0
100
200
300
360
Angle in degrees


Radiation pattern
from VCSEL with checker board PBG
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.001446
0
100
200
300
360
Angle in degrees







The PBG enhanced VCSELs can be designed to outperform electromagnetically the basic oxide-layer model

- Oxide layers negatively effect the output beam patterns
- Lenses can be incorporated naturally
- Output beam patterns are significantly improved with PBG enhancements
- Lower energy output in the side directions decreases potential mutual coupling between radiating elements
- PBG output couplers can produce a flatter wave front
- PBG output coupler can be designed to match VCSEL to a waveguiding structure

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Several PBG waveguide structures for integrated optics applications have been characterized with FDTD Simulations

* FDTD simulator provides a versatile approach to modeling complex PBG structures

* Dielectric input and output waveguides are coupled to triangular PBGs constructed from dielectric and metallic posts

* Defect waveguides formed in the PBG structures are used to construct Y-power splitters

* Control defects are introduced to switch the flow of light

* Reconfigurable PBG splitters and switches may be realizable

Dielectric input and output waveguides are coupled to triangular PBGs constructed from dielectric and metallic posts

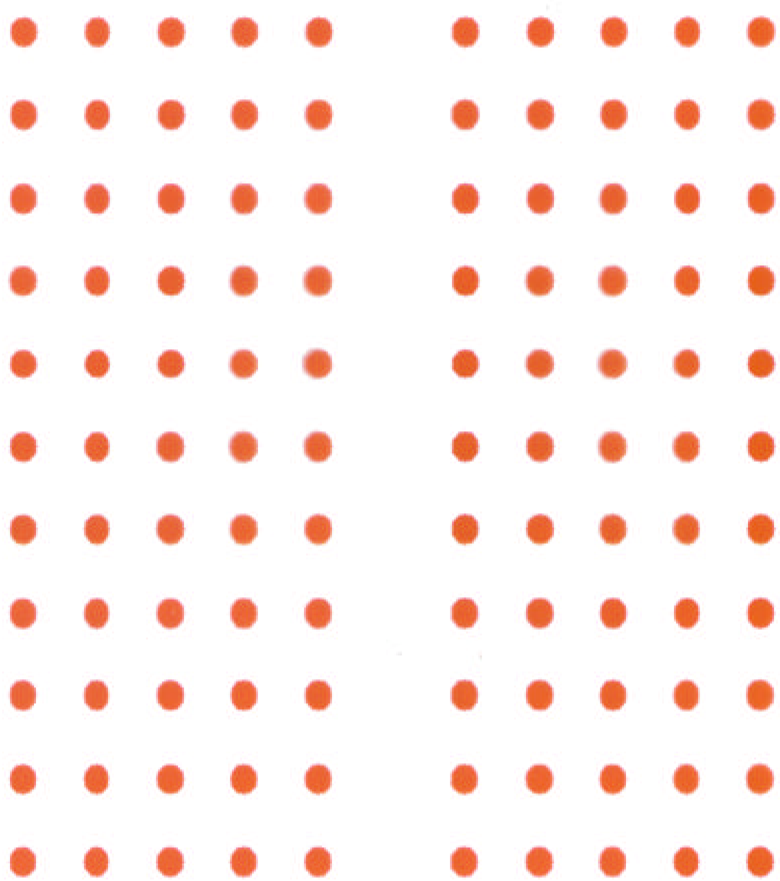
* Structure first driven with ultrafast (6 cycle) pulse to obtain the broadband response

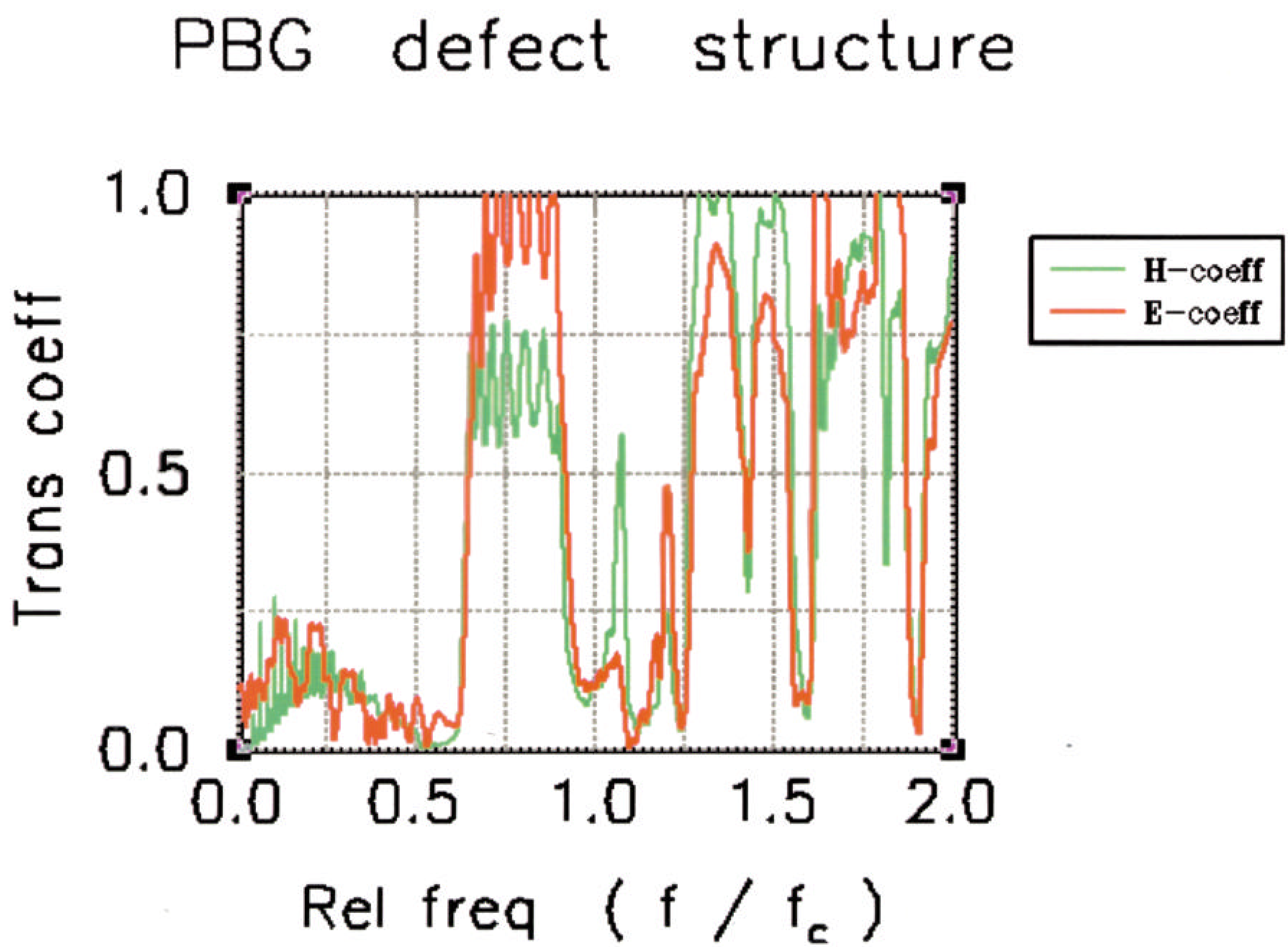
* FFTs of E and H time signals at specified locations lead to the frequency domain spectrums of the input and output powers

* High performance frequencies are identified

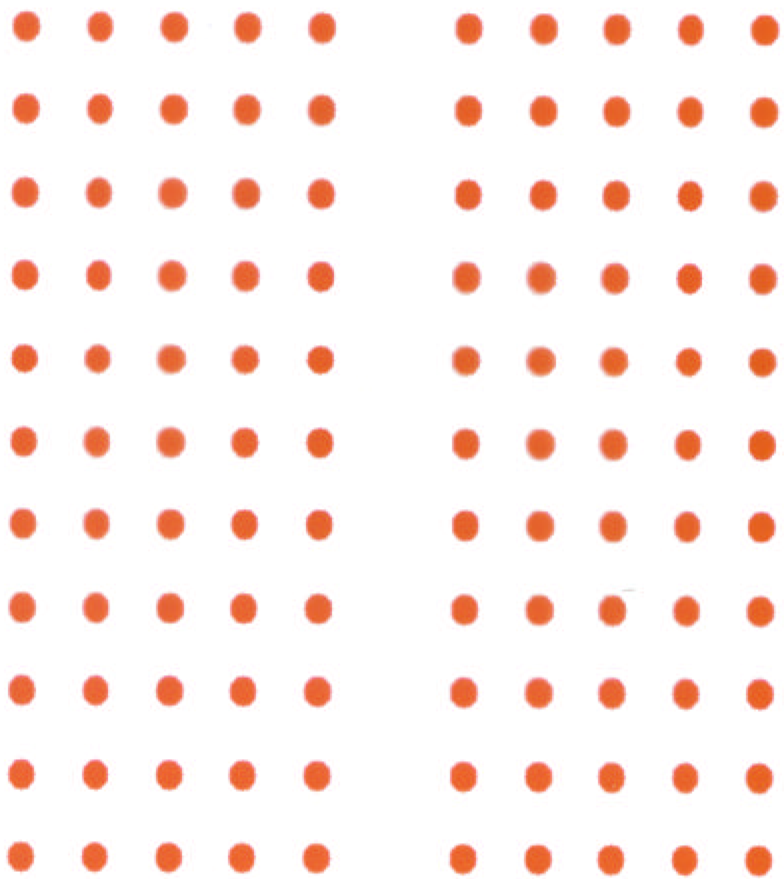
* Structure then driven with many cycles at the "optimum" frequencies to obtain the corresponding narrowband responses

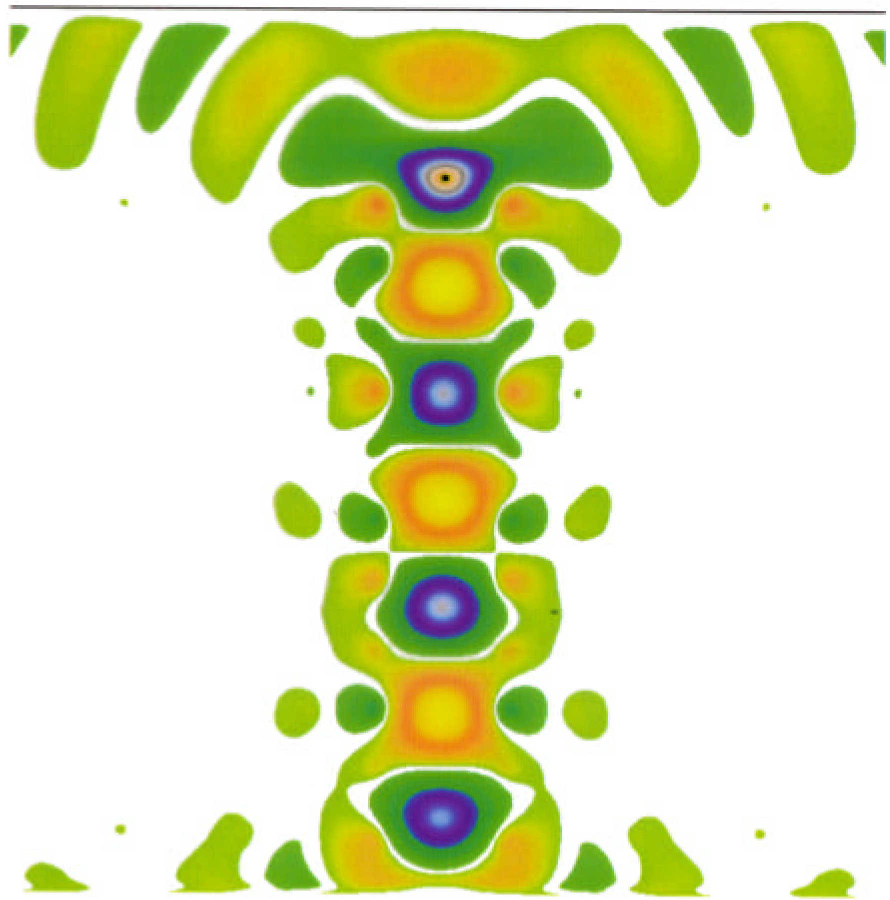
The reflection and transmission properties of the PBG defect structure are obtained with a FDTD simulation driven by a broadband pulse

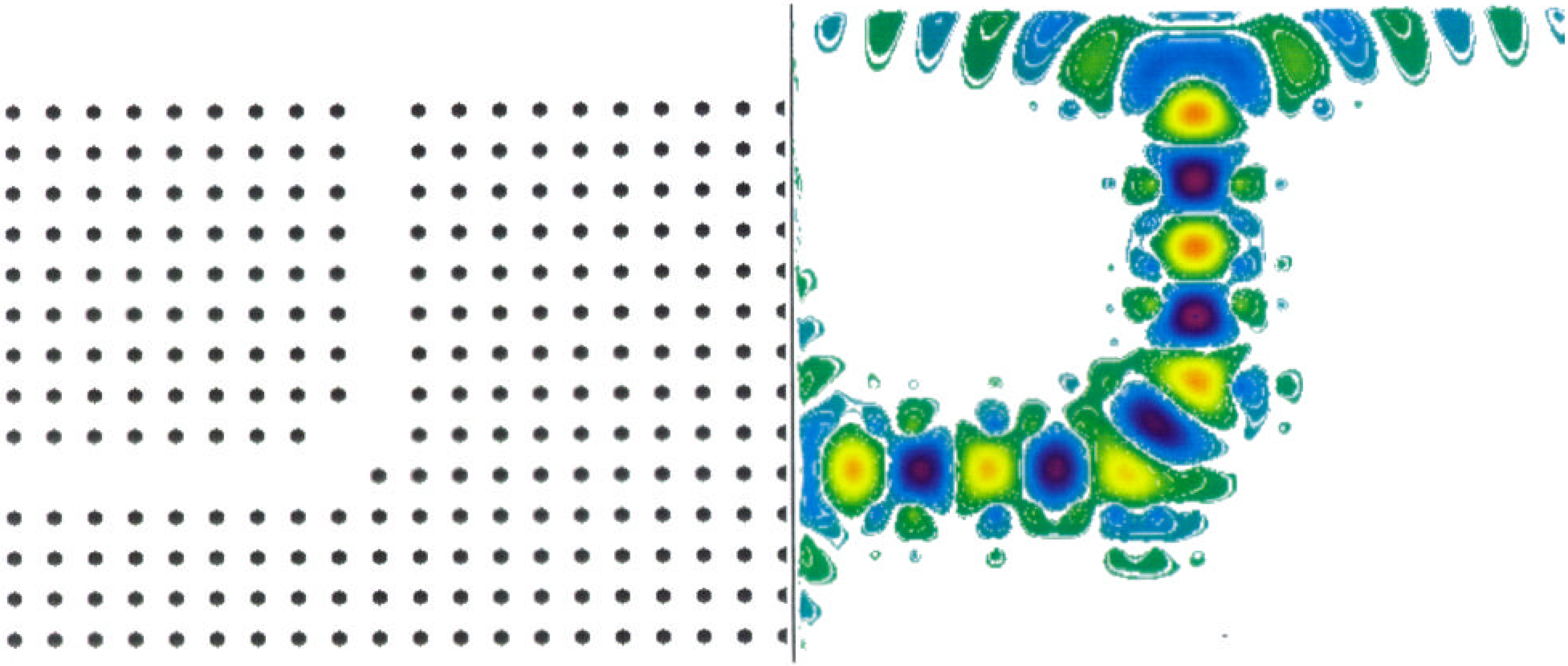



PBG defect structure
Trans coeff
1.0
0.5
0.0
0.0
0.5
1.0
1.5
2.0
Rel freq (f / f_c)
H-coeff
E-coeff

The PBG defect structure provides a useful waveguiding enviroment







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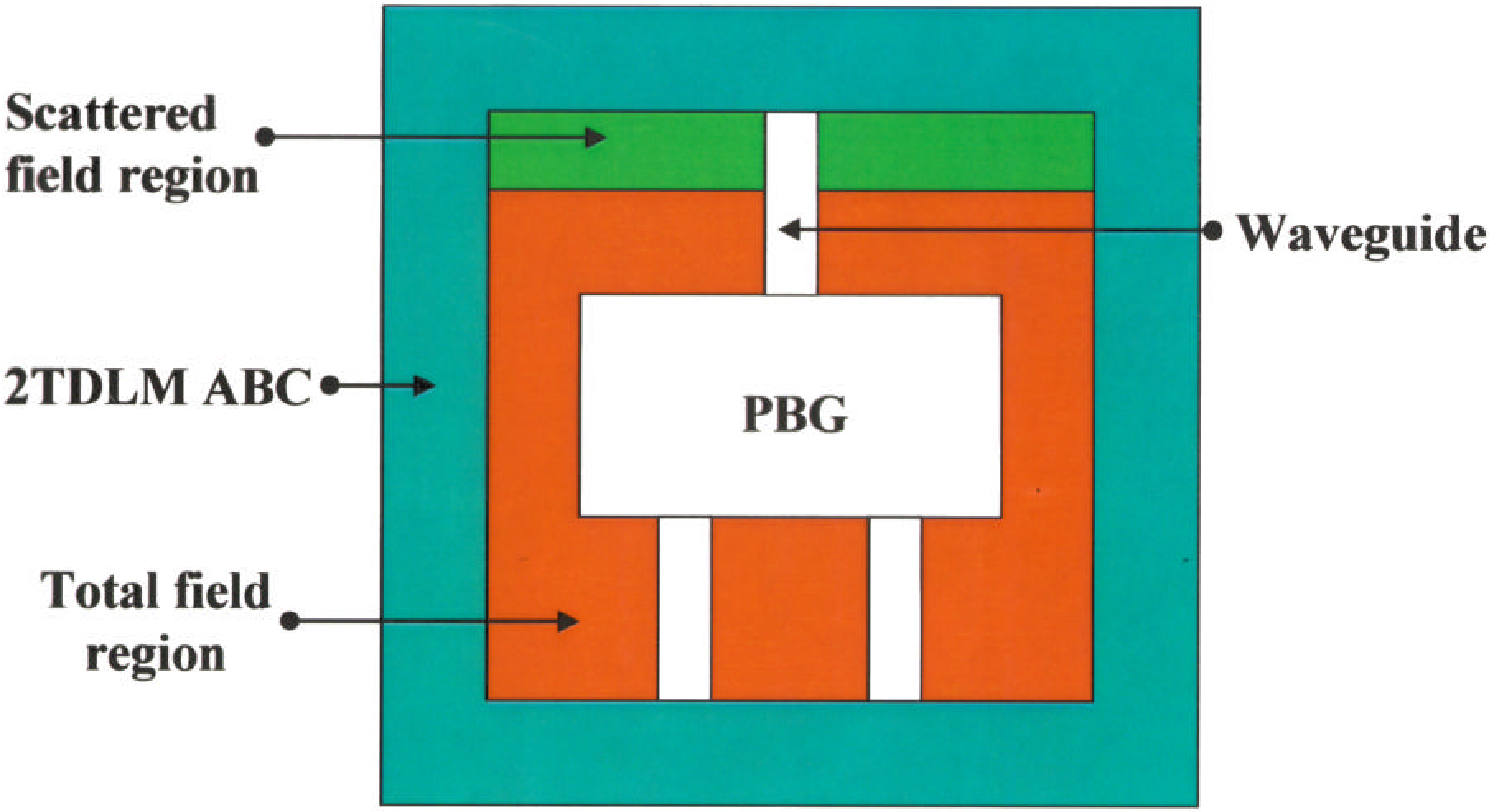
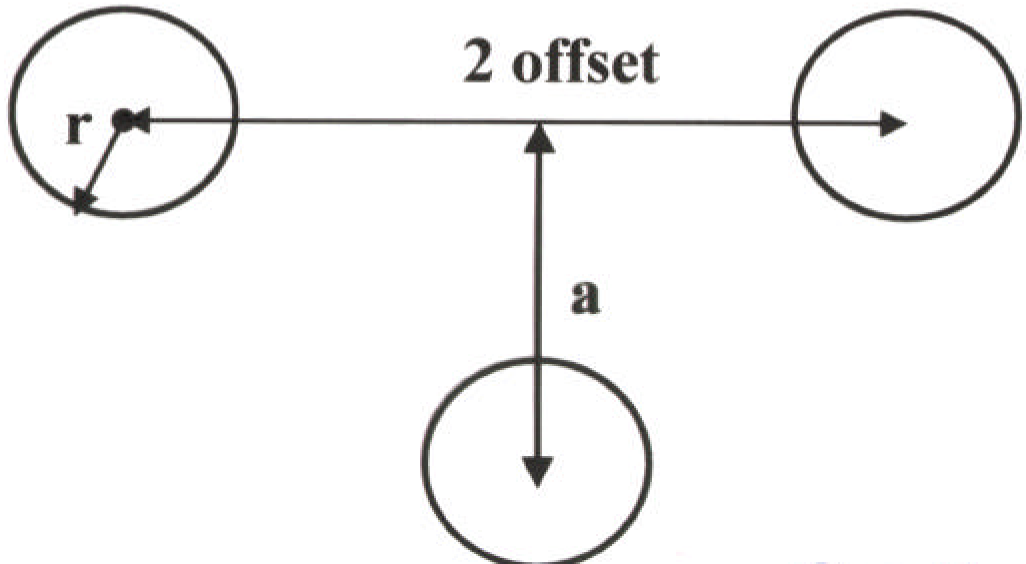
FDTD simulator provides a versatile approach to modeling complex PBG structures



Triangular PBGs were used to achieve a Y-power splitter configuration

Unit cell



Case 1:

$a = 0.5\ \lambda$
offset $= 0.17\ \lambda$
$r = 0.227\ \lambda$

Case 2:

$a = 0.18\ \lambda$
offset $= 0.15\ \lambda$
$r = 0.05\ \lambda$

$\lambda = 1.5\ \mu m$

Defect waveguides formed in the PBG structures are used to construct Y-power splitters

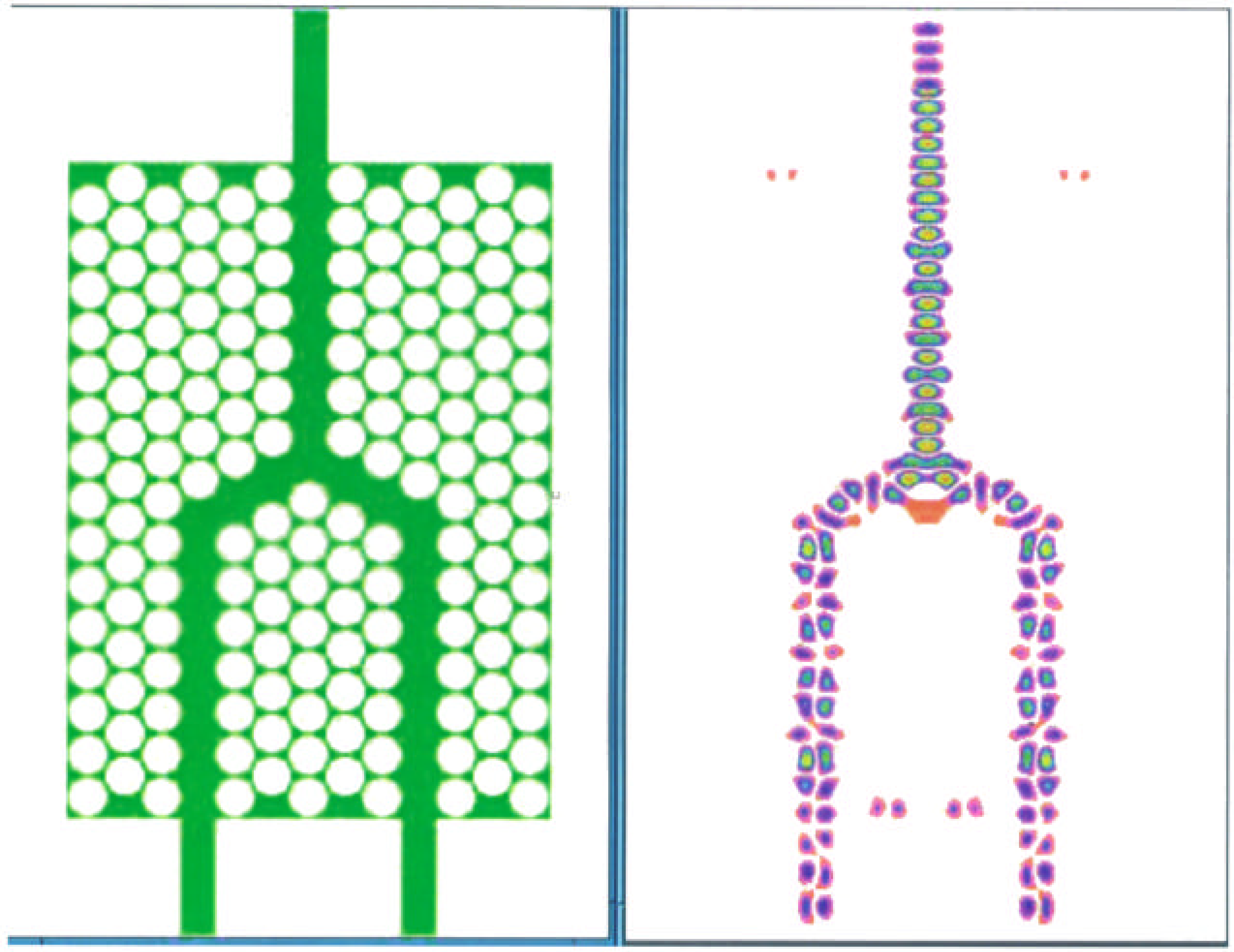
H-pol

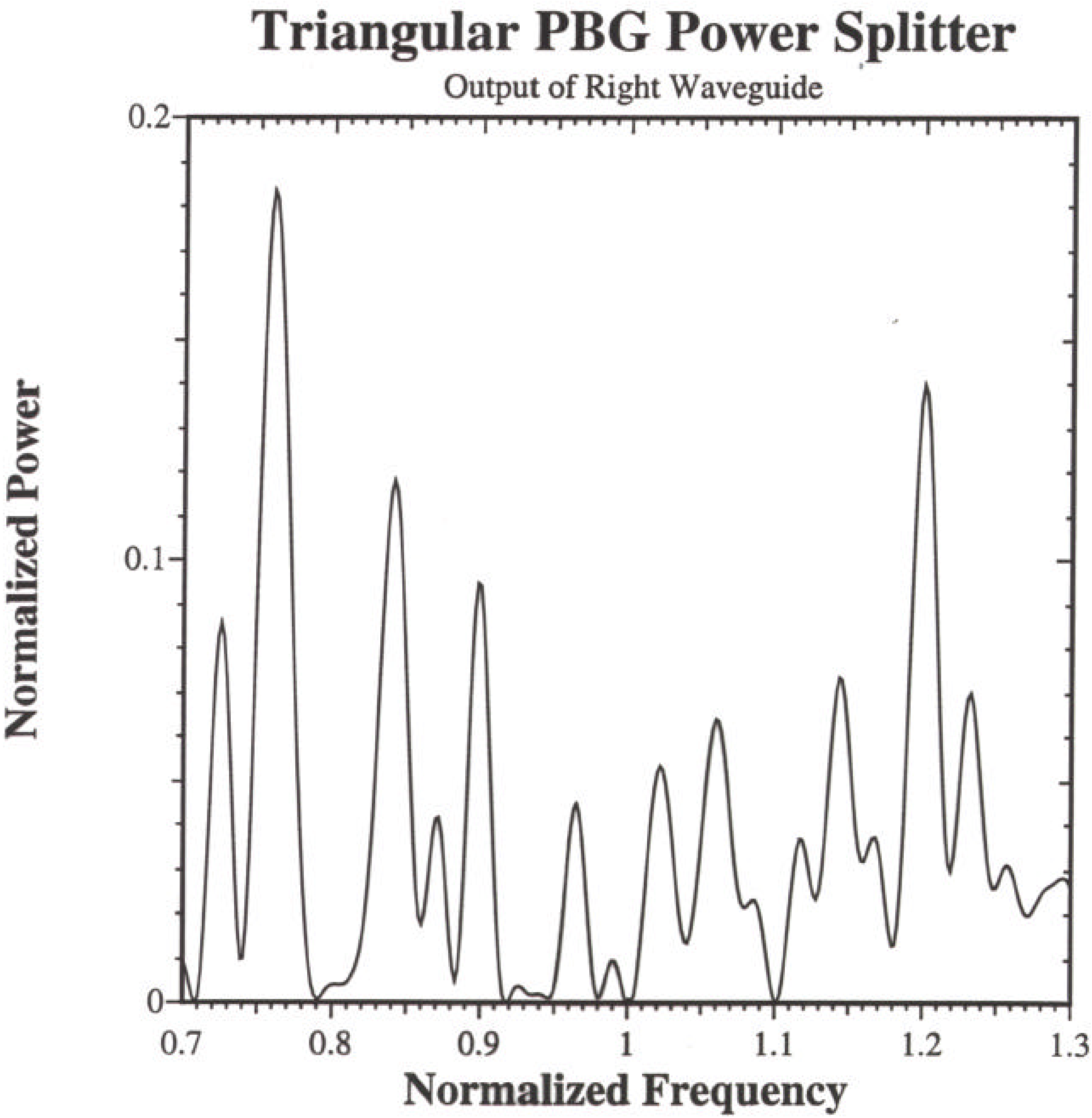
Case 1 PBG air posts

13x30 posts

616x962 cells

10,000 Δ t




Triangular PBG Power Splitter
Output of Right Waveguide
0.2
0.1
0
0.7
0.8
0.9
1
1.1
1.2
1.3
Normalized Power
Normalized Frequency

Control defects are introduced to switch the flow of light

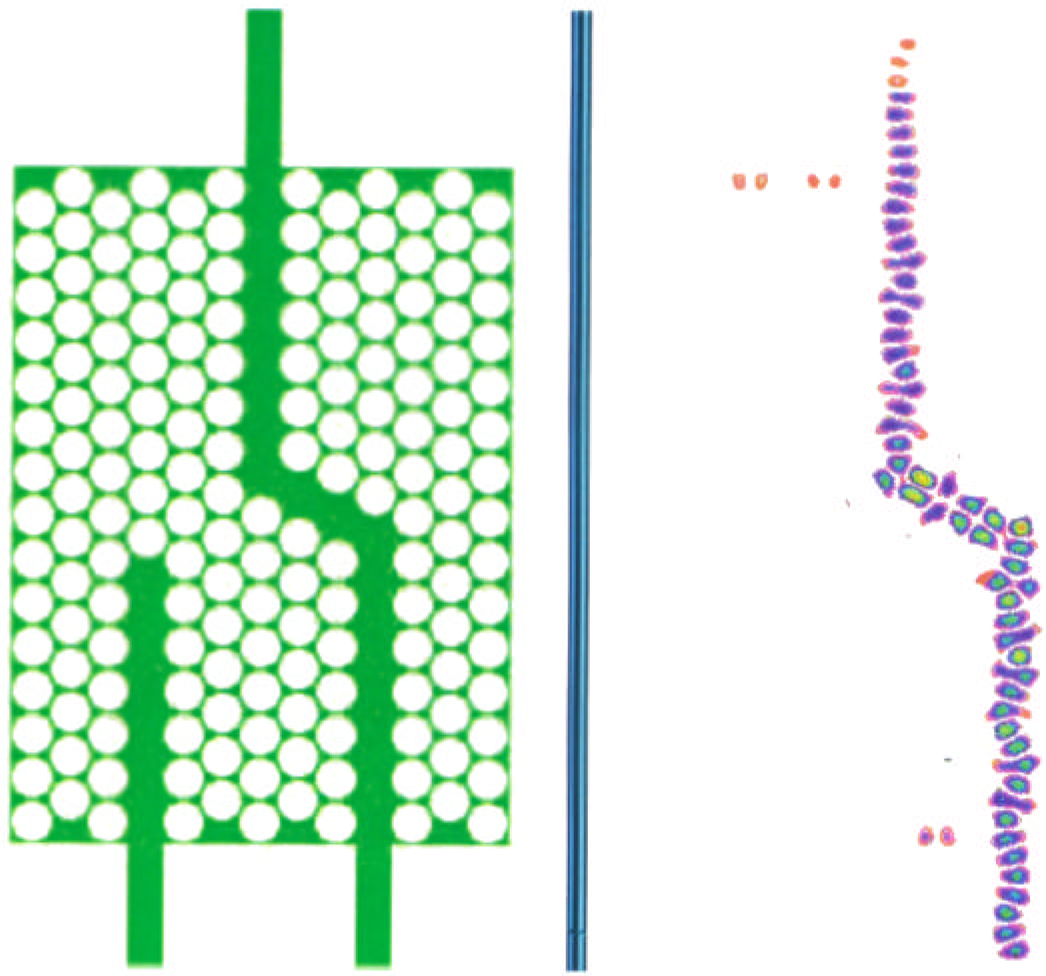
H-pol

Case1 PBG air posts

3 blocking air posts

$f = 0.767\ f_0$

R/L = 808



How does one introduce the control defects ??

* Introduce dielectric rods with a MEMS device - like inserting the control rods into a nuclear pile in a reactor

* Introduce a highly dispersive material whose dielectric constants provide the desired values with a resonance frequency in the pass-band of the PBG - requires a second laser source

* Introduce a metal-like rod by causing a plasma column to form - dielectric breakdown event or a highly doped semiconductor with correct dielectric values needed

Electronically controlled, reconfigurable PBG structures may be realizable

Reconfigurable PBG splitters and switches may be realizable

E-pol

Case 2 PBG
metal posts

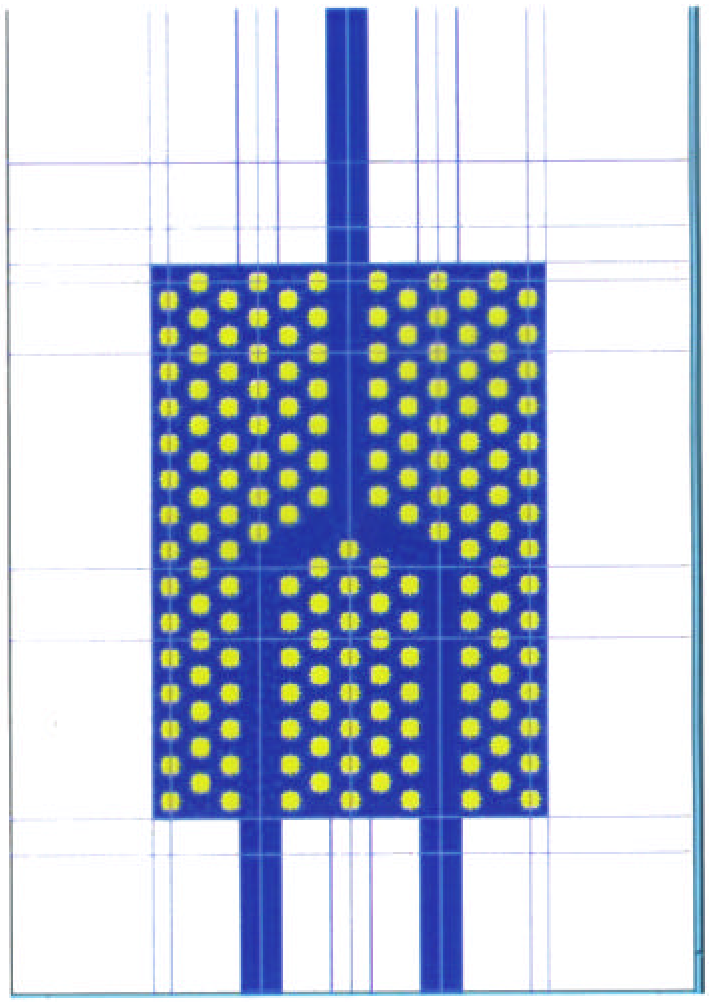
13x30 posts

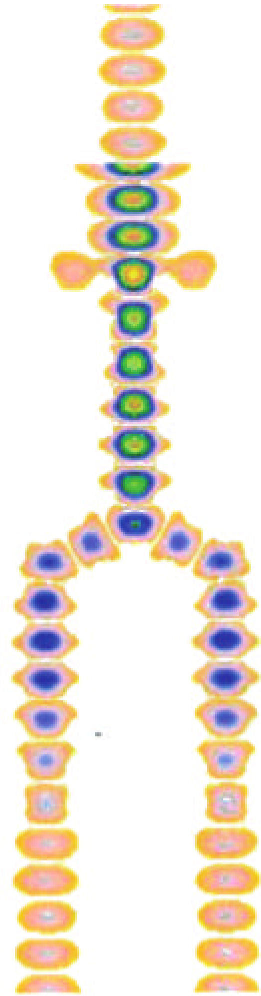
340x538 cells

10,000 Δt

$f = 0.937 f_0$

$T = 4.05\%$





Reconfigurable PBG splitters and switches may be realizable

E-pol

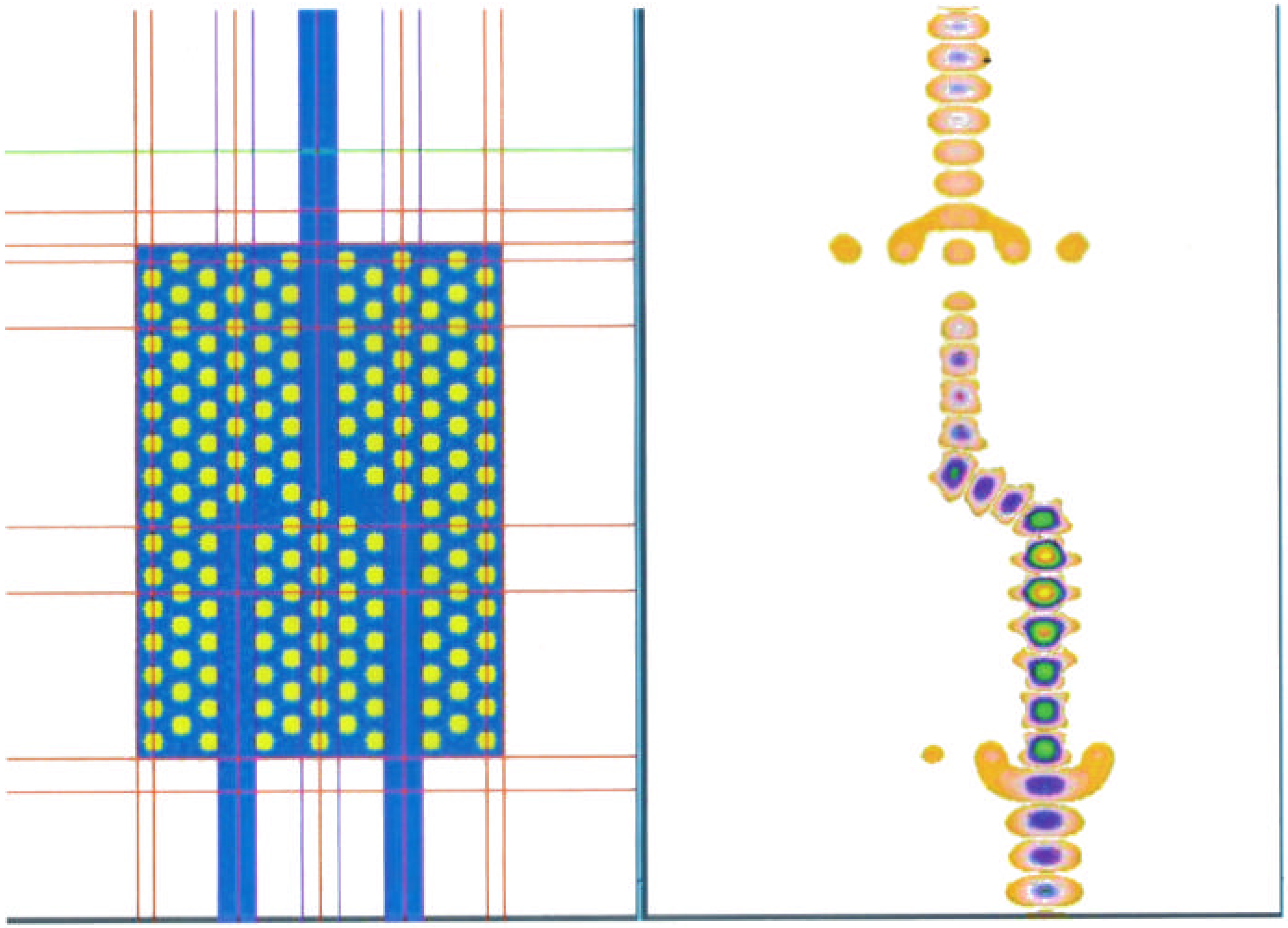
Case 2 PBG metal posts

1 blocking metal post

$f = 0.937\ f_0$

T = 8.10 %

R/L = 1643



The two-dimensional TE Maxwell-Bloch system is

The electric and magnetic fields and the polarization components are solved self-consistently:

TE Maxwell equations

$$\partial_t H_x = +\frac{1}{\mu_0} \partial_z E_y \tag{1a}$$

$$\partial_t H_z = -\frac{1}{\mu_0} \partial_x E_y \tag{1b}$$

$$\begin{aligned}\partial_t E_y &= \frac{1}{\epsilon_0} (\partial_z H_x - \partial_x H_z) - \frac{1}{\epsilon_0} \partial_t P_y \\ &= \frac{1}{\epsilon_0} (\partial_z H_x - \partial_x H_z) - \frac{N_{atom}\, \gamma}{\epsilon_0\, T_2} \rho_1 + \frac{N_{atom}\, \gamma\, \omega_0}{\epsilon_0} \rho_2 \end{aligned} \tag{1c}$$

Bloch equations

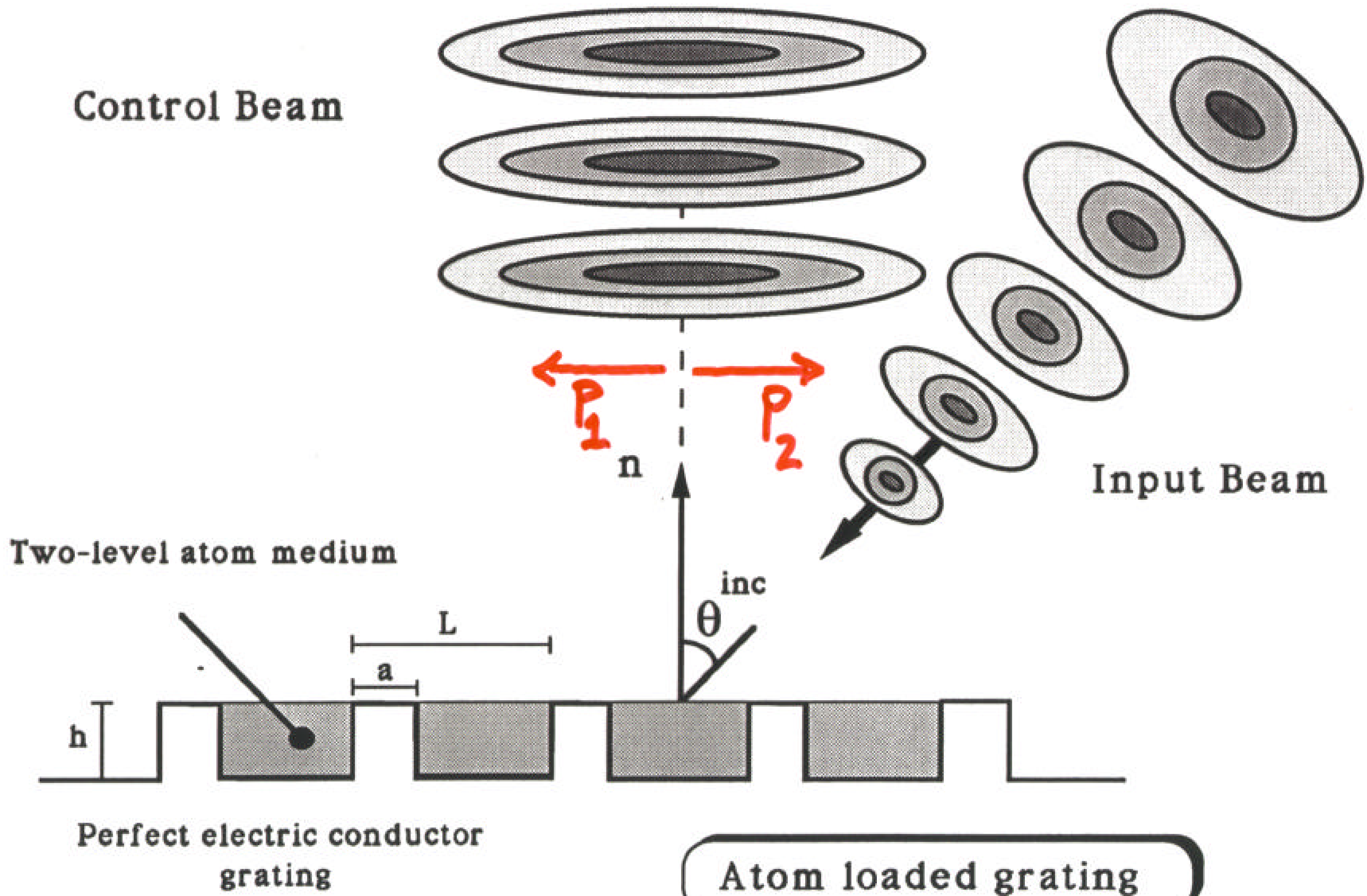
$$\partial_t \rho_1 = -\frac{1}{T_2} \rho_1 + \omega_0 \rho_2 \tag{2a}$$

$$\partial_t \rho_2 = -\omega_0 \rho_1 - \frac{1}{T_2} \rho_2 + 2 \frac{\gamma}{\hbar} E_y \rho_3 \tag{2b}$$

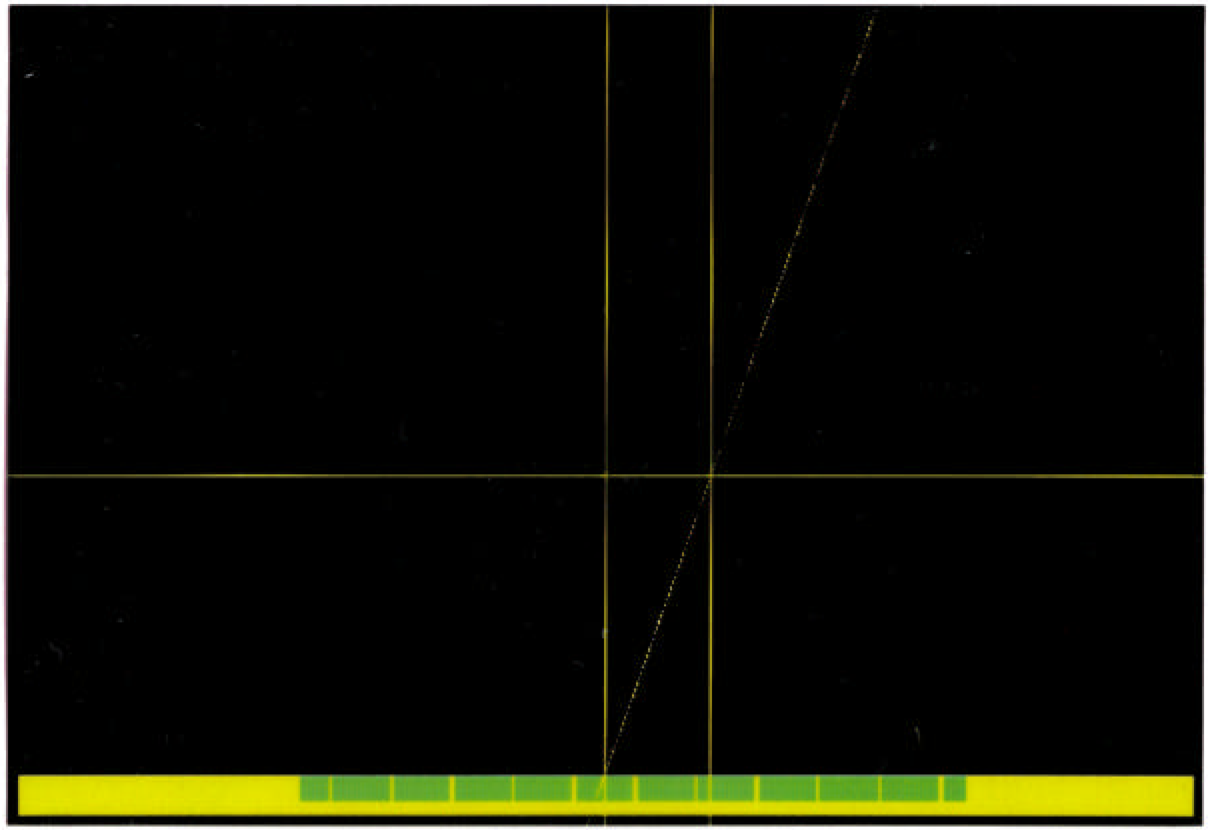
$$\partial_t \rho_3 = -2 \frac{\gamma}{\hbar} E_y \rho_2 - \frac{1}{T_1} (\rho_3 - \rho_{30}) \tag{2c}$$

This system has been implemented successfully with the predictor-corrector scheme

Optical Triode Configuration

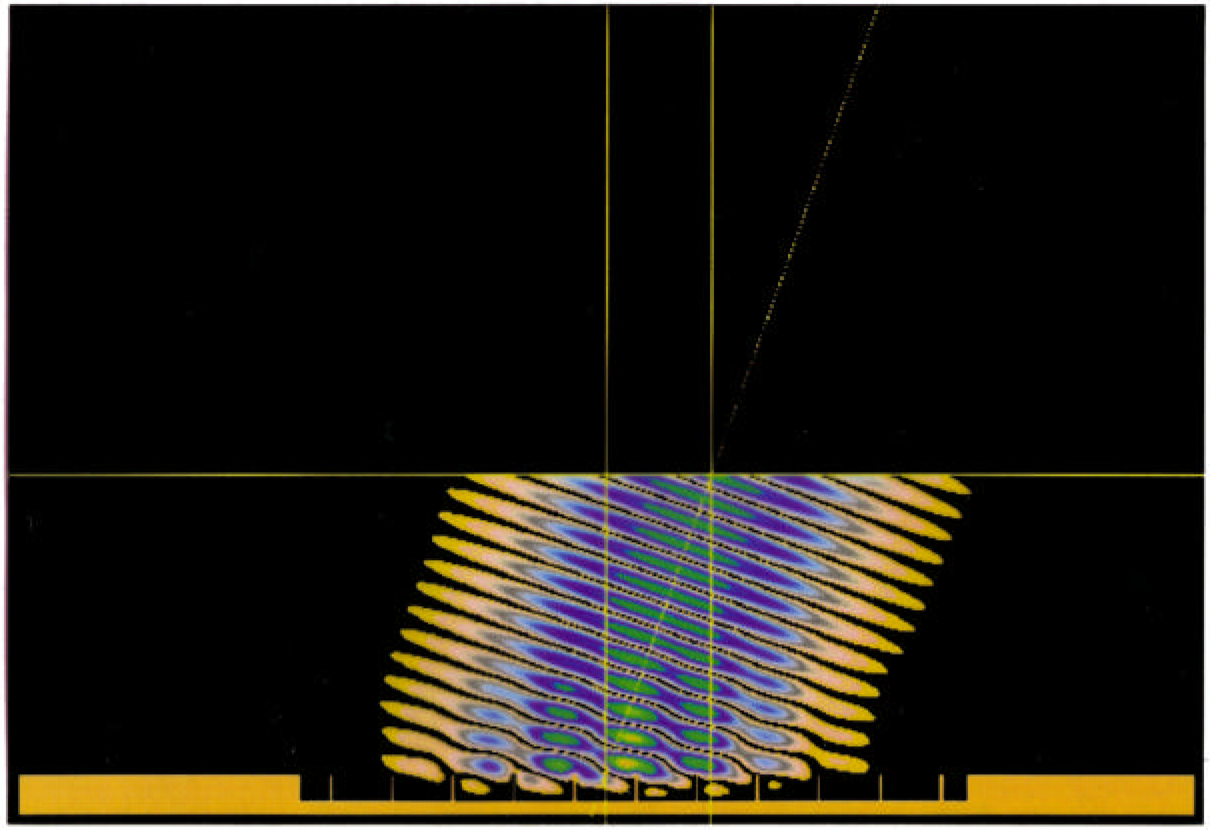


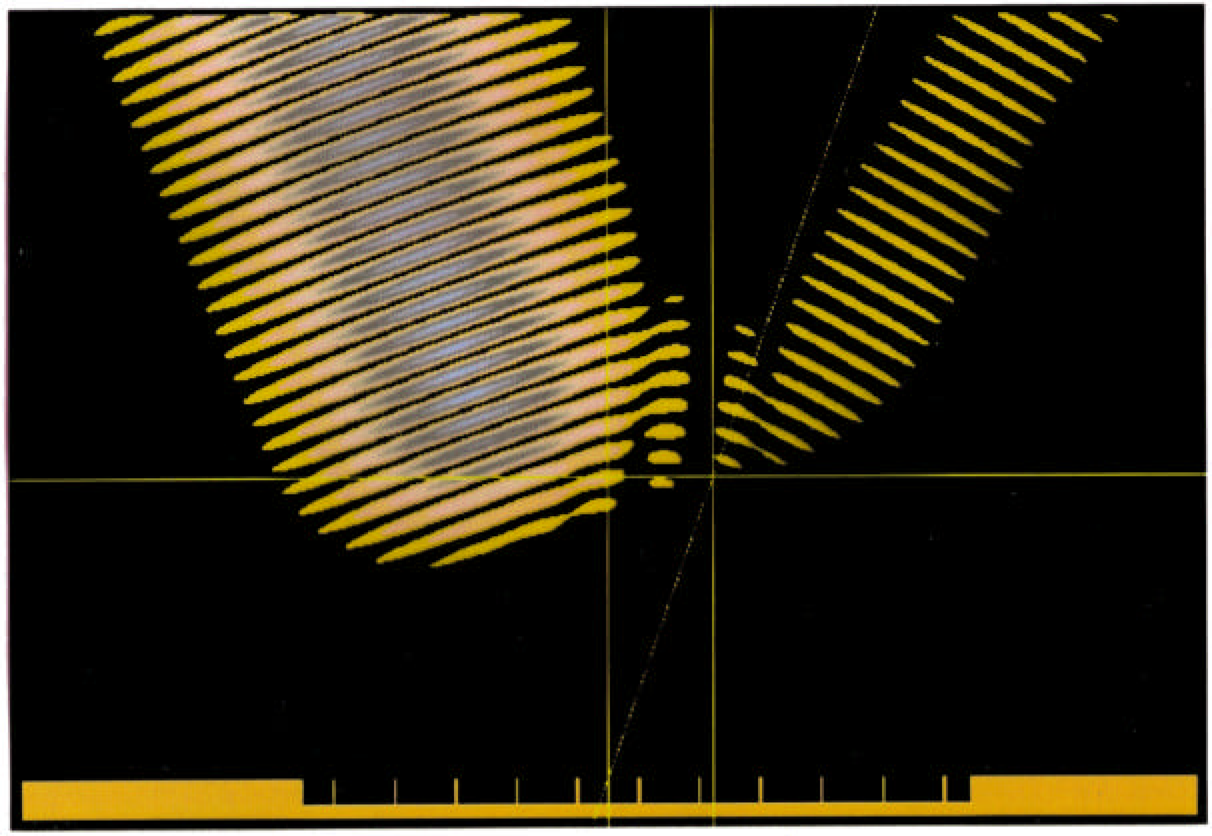
Atom loaded grating



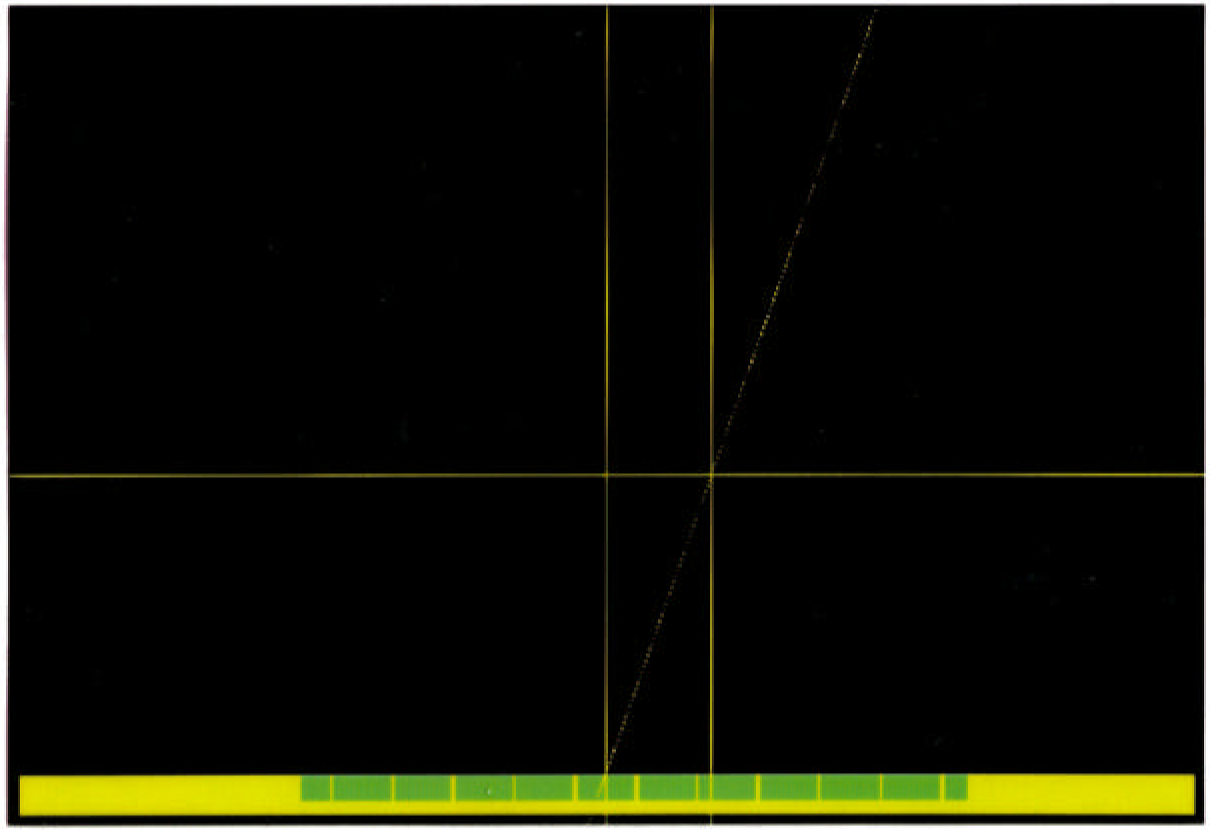
A Gaussian beam is incident upon a grating loaded with two level atoms in their ground state

UD MURI



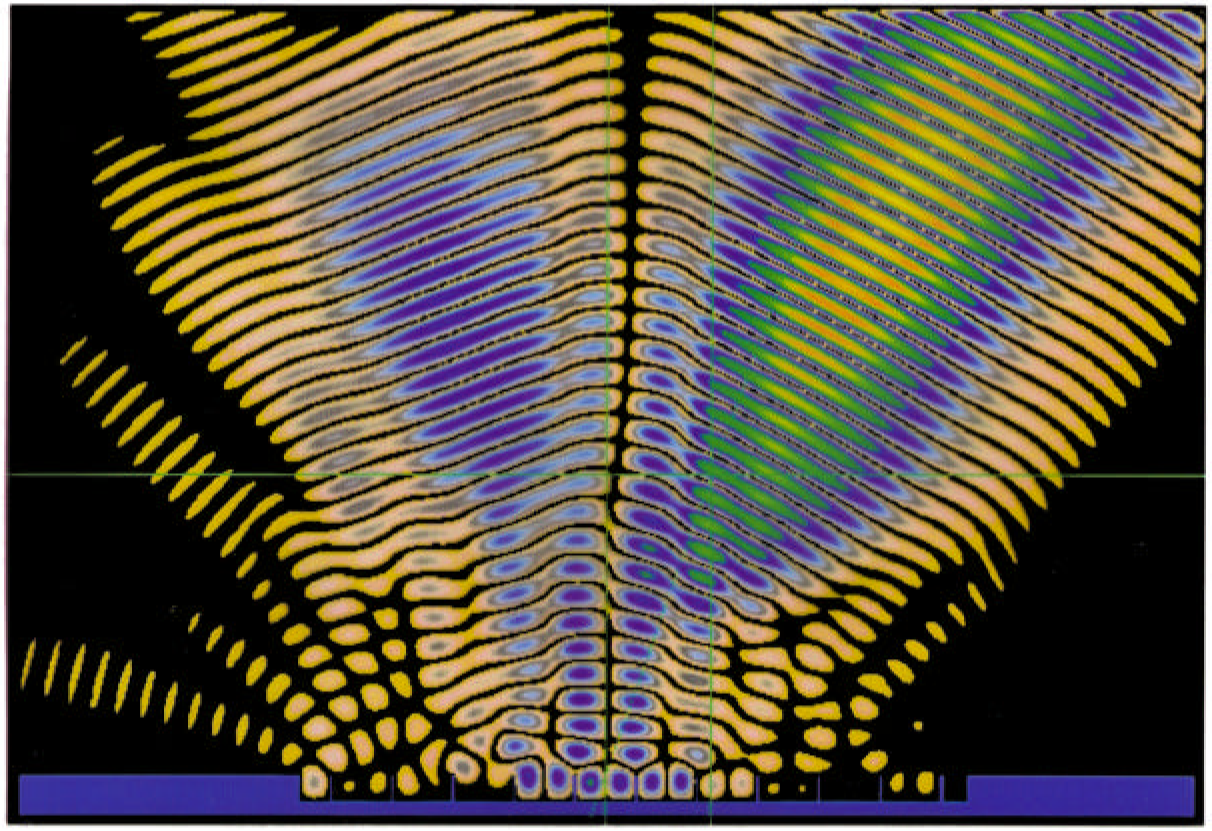


The loaded grating acts as a reflector and the Gaussian beam is reflected away from the source



A Gaussian beam is incident upon a grating loaded with two level atoms in their excited state

MURI



The loaded grating is now penetrable so the Gaussian beam is reflected towards the source and the excited atoms give up their energy to the beam causing power amplification

UD MURI

The radiation patterns are readily obtained with a near-to-far-field transform and confirm the desired triode switching behavior