The University of Tokyo

Simulation of Phase Dynamics in Active Multimode Interferometers

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Outline

1. Introduction
2. Previous static simulation and experimental results
3. Details of the proposed method for dynamic simulation
4. Recent results
5. Conclusion

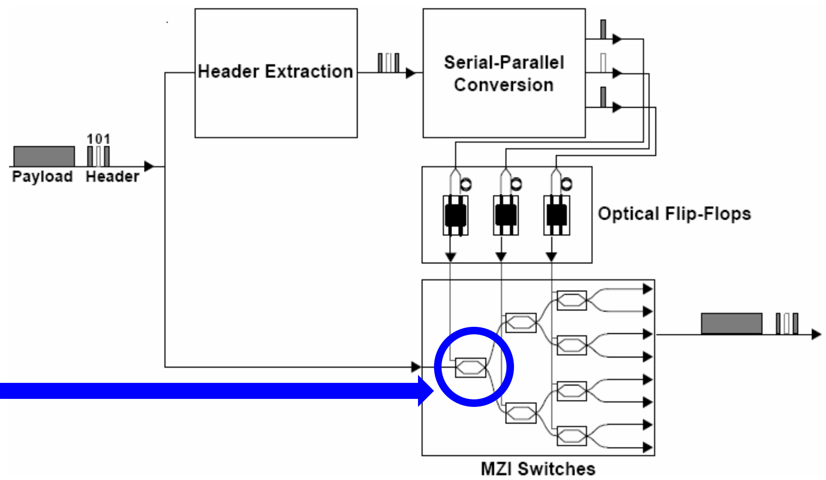
All-optical Switches for integration

Throughput of routing nodes is a bottleneck that has to be addressed

Several proposals for an all-optical node to enable all-optical packet switching

An all-optical switch based on MZI plays a main role, could this role be extended

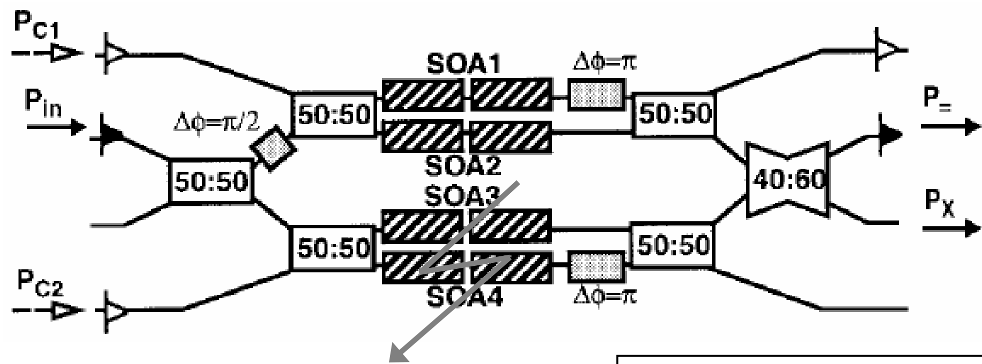
An all-optical switch suitable for high-density integration is demanded



* M. Takenaka et. al, OFC'06

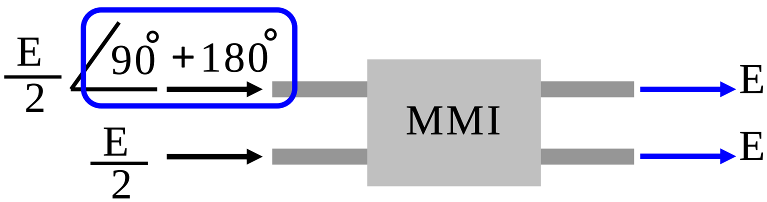
Introducing an MMI to the all-optical switch

An all-optical switch with interleaved interferometers on each arm

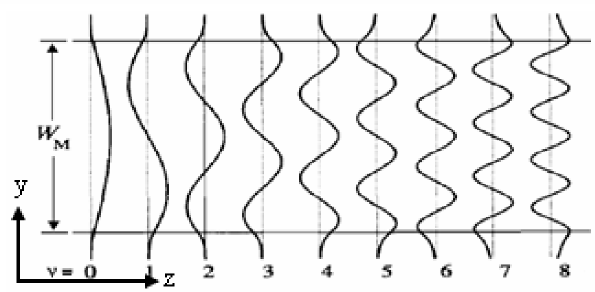


J. Leuthold et. al, *J. Lightwave Technol., 1999*

Multimode interferometer (MMI)



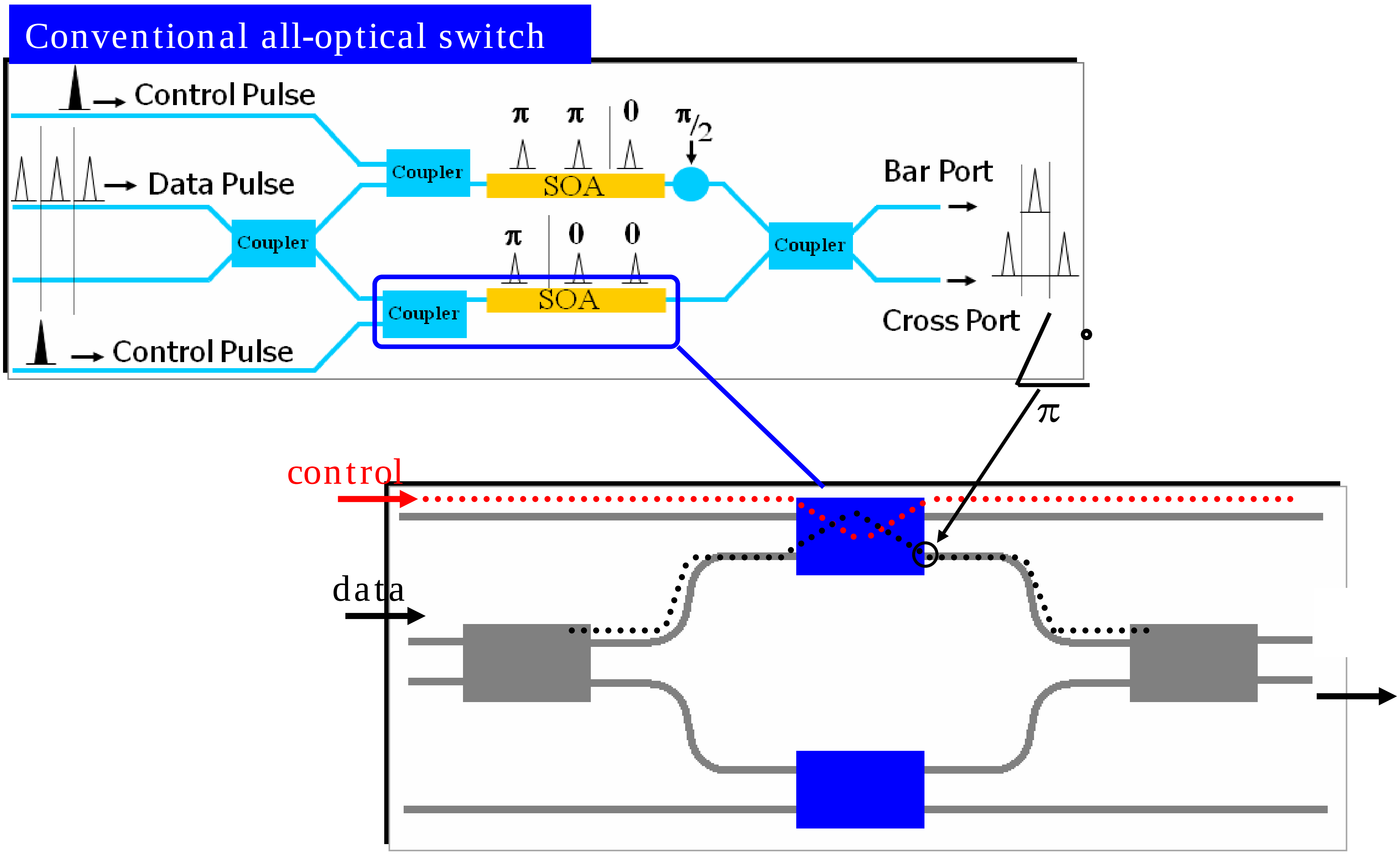
$$\psi(y,z) = \sum_{\nu=0}^{\nu=m-1} c_\nu \varphi_\nu(y) \exp\left[j \frac{\nu(\nu-2)\pi}{3L_\pi} z \right]$$



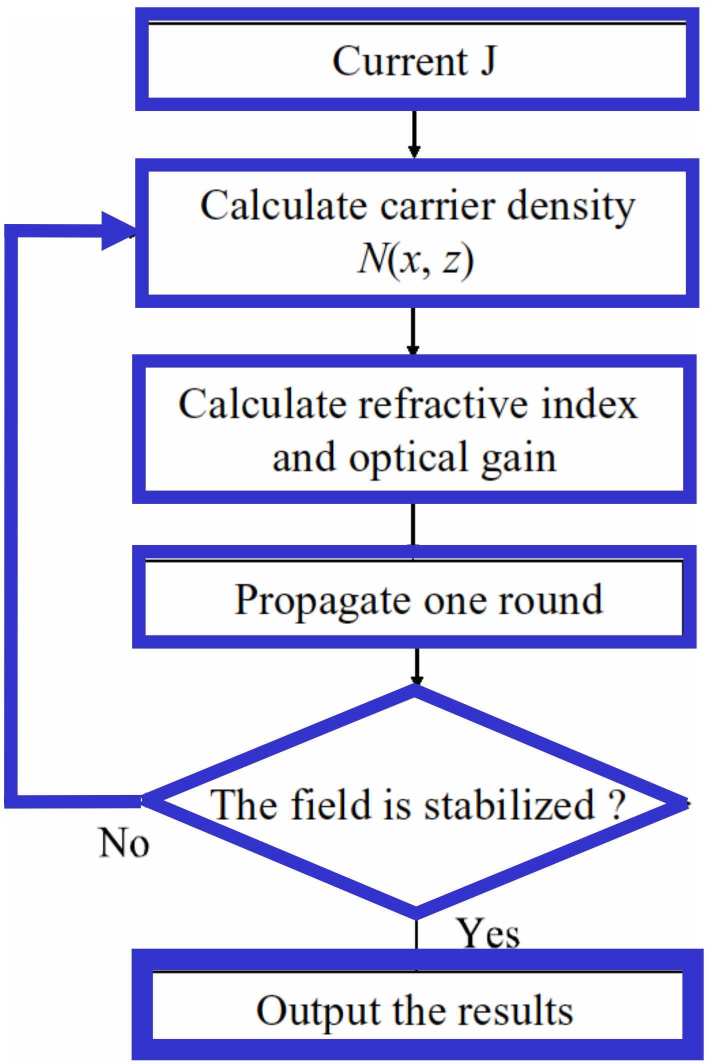
Properly designed MMI couplers can enable

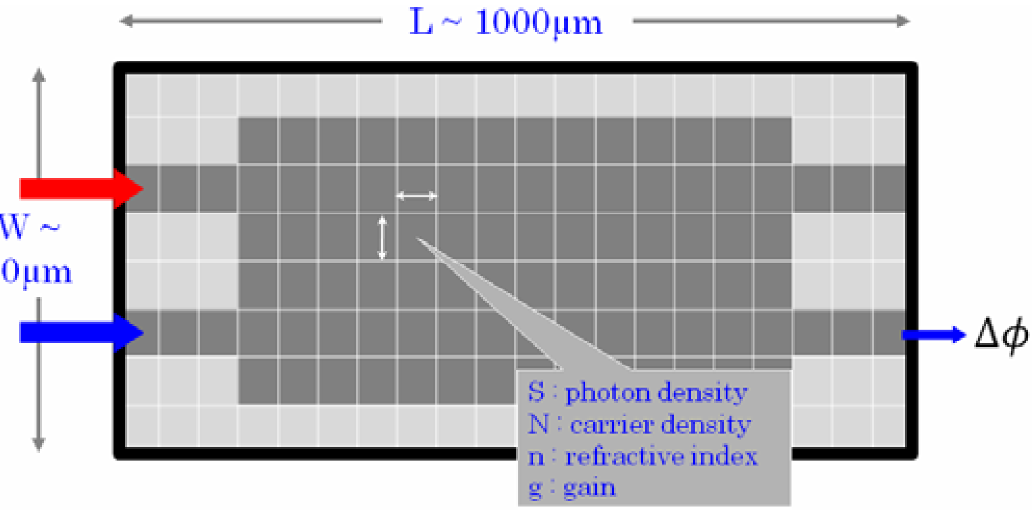
- Signals combination & separation
- Controllable Direction of input to a specific output by phase adjustment
- Directing different inputs to different outputs after interaction

Novel Switch based on Active MMI



Simulation algorithm *



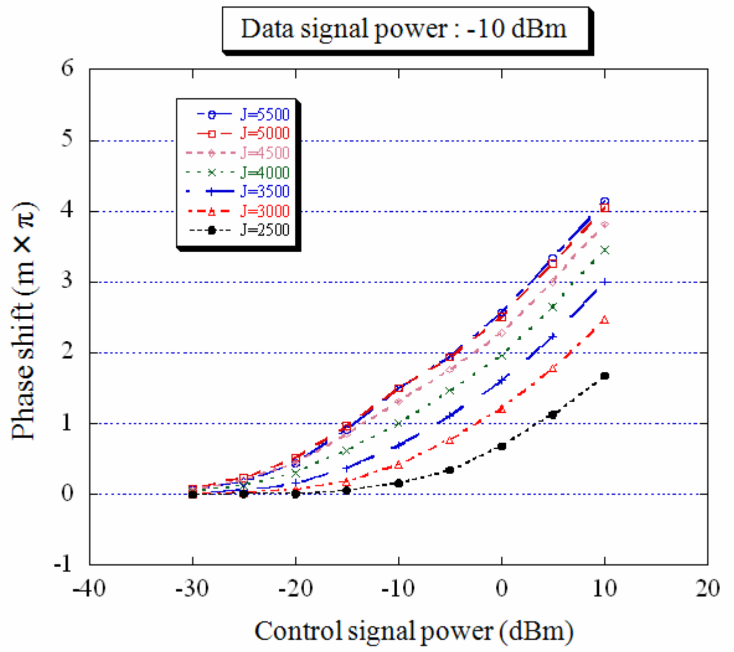


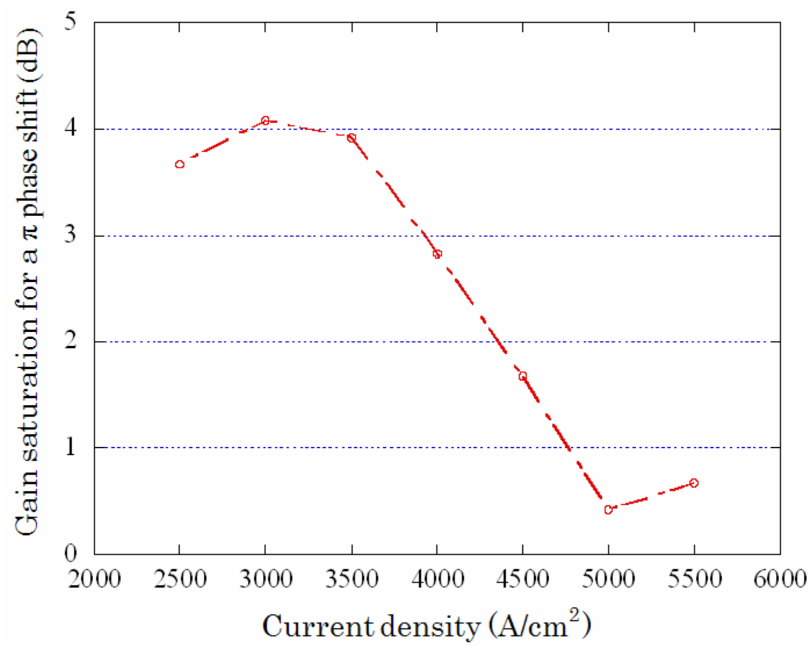
$$\frac{J}{ed} = R(N) + \Gamma v_g g_1 S_1 + \Gamma v_g g_2 S_2$$

$$\begin{cases} n = n_0 + \dfrac{dn}{dN} N \\ g_0(N) = a(N - N_0) \\ g_1(N) = \dfrac{g_0}{1 + \varepsilon_{11} S_1 + \varepsilon_{12} S_2} \\ g_2(N) = \dfrac{g_0}{1 + \varepsilon_{22} S_2 + \varepsilon_{21} S_1} \end{cases}$$

$$2j\beta_o \frac{\partial \varphi}{\partial z} = \frac{\partial^2 \varphi}{\partial x^2} + (k_o^2 n^2 - \beta_o^2)\varphi$$

Simulation results for XPM and XGM





Simulation results support the validity of the new idea

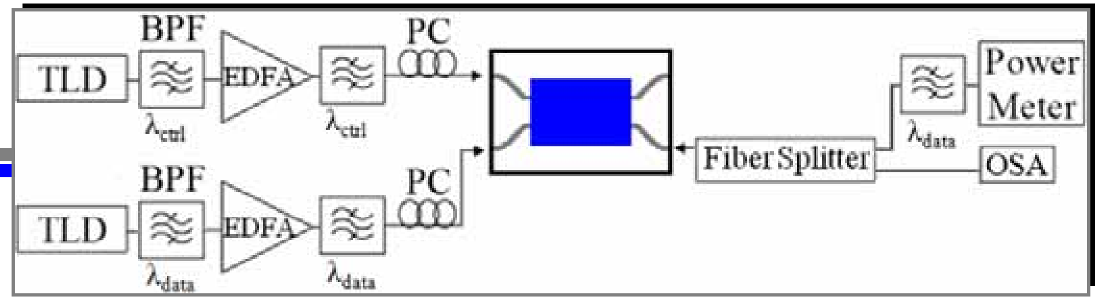
The data signal self-imaging is not disturbed by inserting the ctrl signal.

An enough phase shift [through XPM] is obtainable at achievable values of injected current density and optical powers.

An associated XGM is present and can be made low.

The XPM increases by decreasing the data signal power.

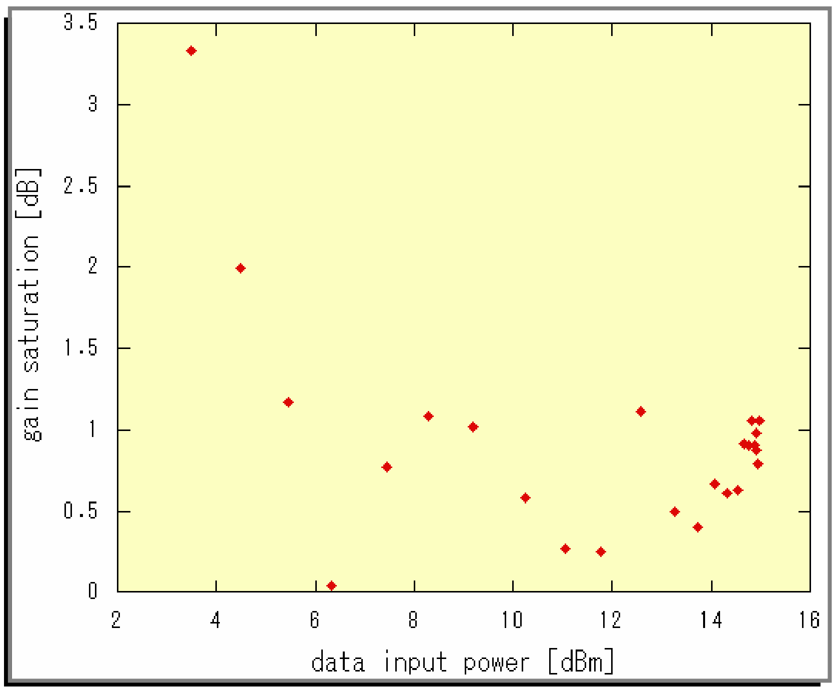
Measurement of XGM

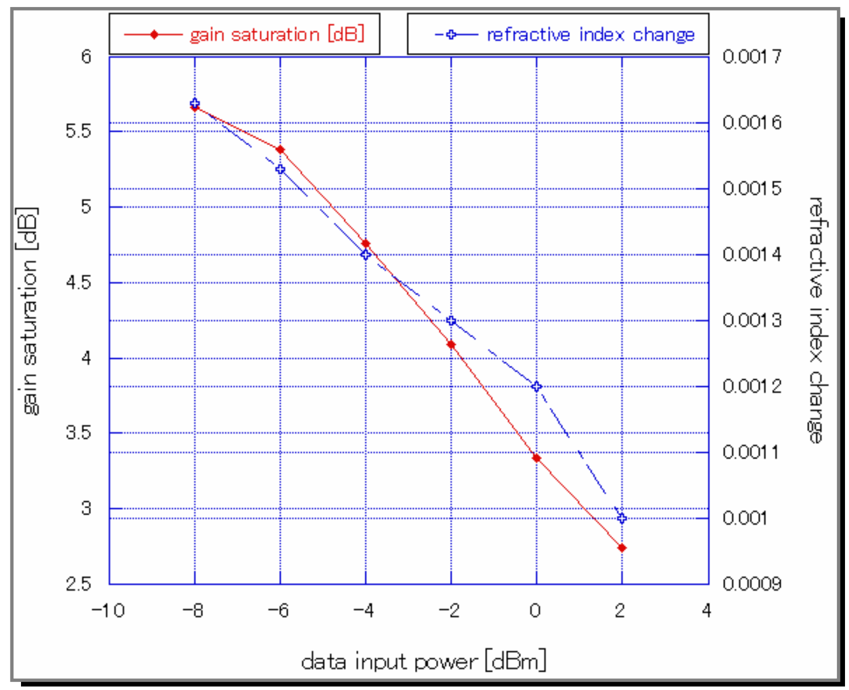


Control signal wavelength : 1543 nm (Peak power for EDFA)

Control signal Power : 15 dBm at fiber tip ----> 4 dBm at active part

Measurement is done first with a control signal then without





S. Ibrahim et. al, Photonics in switching'08

Analysis of phase dynamics in active MMI

Need for dynamic analysis

What is the effect of the spatial hole burning on the device performance

Quantitatively, how much pulse energy is required for enough XPM

How long is the recovery time of the active MMI

…..

Need to have a fast and reliable way of solution

Solve the carrier rate equation together with the wave equation in 2D and time

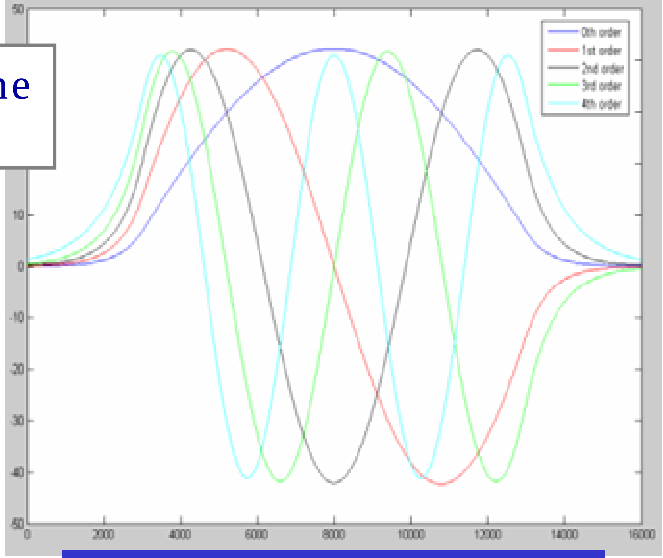
- Time resolution should be 1/5 of one optical cycle ?!!!

Repeat the steady state analysis in time (previous algorithm)

- Time and storage problem
- The origin of XPM is not rigorously included
- Modal insight is absent

Basic formulation of the problem (1)

1. Optical fields are modeled by the modes excited in the active MMI



Profiles of optical mode

$$E(x,y,z,t) = \sum_n A_n(z,t)\, b_n(x,y)\, exp\,(\omega t - k_n z)$$

$$A_n(z,t) = \sqrt{P_n} \cdot exp\,(i\varphi_n)$$

1. For a given injected current density, the carrier density is calculated by solving the steady state carrier rate equation.
2. Assuming a given value for the alpha factor, the change in the refractive index of the active MMI (n_core) is found.
3. For the new value of n_core, the eigenvalue problem of the MMI is solved and hence bn is found.
4. The group velocity is calculate d according to [5*].
5. The initial value of Pn is found by matching the modes to the exciting input.

Basic formulation of the problem (2)

2. An approximate lateral distribution is used to model the carrier density

$$N(x,z) = N_{avg}(z,t) + N_1(z,t)F_1(x) + N_2(z,t)F_2(x) + \cdots + N_m(z,t)F_m(x)$$

A separate rate equation for each carrier profile coefficient

We only consider a narrow active MMI whose width is less than 12 um.

The optical intensity decreases with the increase of the optical mode order

The carriers non-uniformities wash out faster with shorter spaced disturbances

For a 1x1 active MMI

$$N(x,z) = N_{avg}(z,t) + N_1(z,t)\cos\left(\frac{2\pi x}{W}\right) + N_2(z,t)\cos\left(\frac{4\pi x}{W}\right) + N_3(z,t)\cos\left(\frac{6\pi x}{W}\right)$$

For a 2x2 active MMI

$$N(x,z) = N_{avg}(z,t) + N_1(z,t)\cos\left(\frac{2\pi x}{W}\right) + N_2(z,t)\sin\left(\frac{2\pi x}{W}\right) + N_3(z,t)\cos\left(\frac{4\pi x}{W}\right) + N_4(z,t)\sin\left(\frac{4\pi x}{W}\right)$$

The carrier density coefficients' update equations

$$\frac{\partial N}{\partial t} = D\frac{\partial^2 N}{\partial x^2} + \frac{J}{ed} - R(N) - g(N)\frac{I}{\hbar\omega}$$

$$R(N) = AN + BN^2 + CN^3$$

N	Total Carrier density
D	Diffusion coefficient
J	Injected current density
g	Optical gain
I	Optical intensity
R	Carrier recombination rate

To find Navg

$$\frac{\partial N_{avg}}{\partial t} = \frac{1}{wd}\iint\left(D\frac{\partial^2 N}{\partial x^2} + \frac{J}{ed} - R(N) - g(N)\frac{I}{\hbar\omega}\right)dx.dy$$

$$for \quad N(x,z) = N_{avg}(z,t) + N_1(z,t)\cos\left(\frac{2\pi x}{W}\right) + N_2(z,t)\cos\left(\frac{4\pi x}{W}\right)$$

assuming 2 modes (for example)

$$I = b_0^2(x)P_0 + b_2^2(x)P_2 + 2b_o(x)b_2(x)\sqrt{P_0P_2}\cos(\phi_{0,2})$$

$$\iint g(N).I\,dxdy = aN_{th}\cdot\Gamma_y\cdot\begin{bmatrix}(N'_{avg}-1)\cdot\left(\overline{b_0^2}P'_0 + \overline{b_2^2}P'_2 + 2\overline{b_0b_2}\cdot\sqrt{P'_0P'_2}\cos(\phi_{0,2})\right)\\ +N'_1\cdot\left(\overline{F_1b_0^2}P'_0 + \overline{F_1b_2^2}P'_2 + 2\overline{F_1b_0b_2}\cdot\sqrt{P'_0P'_2}\cos(\phi_{0,2})\right)\\ +N'_2\cdot\left(\overline{F_2b_0^2}P'_0 + \overline{F_2b_2^2}P'_2 + 2\overline{F_2b_0b_2}\cdot\sqrt{P'_0P'_2}\cos(\phi_{0,2})\right)\end{bmatrix}$$

$$where,\ \overline{F_mb_ib_j} = \int F_m(x)\,b_i(x)b_j(x)\cdot dx\ ,\quad N'_m = N_m/N_{th} \quad \& \quad P'_n = \frac{P_n/E_{sat}}{\hbar\omega}$$

All overlapping coefficients are calculated before the program run time

Update equation for carrier density coefficients (2)

Overlapping coefficients for 4 modes and 2 carrier distributions

$\overline{b_0^2}$	0.9973	$\overline{F_1 b_0^2}$	-0.4165	$\overline{F_2 b_0^2}$	~~2.6170e-004~~
$\overline{b_1^2}$	0.9889	$\overline{F_1 b_1^2}$	0.1401	$\overline{F_2 b_1^2}$	~~8.8041e-005~~
$\overline{b_3^2}$	0.9475	$\overline{F_1 b_3^2}$	0.0832	$\overline{F_2 b_3^2}$	~~5.2208e-005~~
$\overline{b_4^2}$	0.9014	$\overline{F_1 b_4^2}$	0.0620	$\overline{F_2 b_4^2}$	~~3.8873e-005~~
$2\overline{b_0 b_1}$	~~3.6962e-005~~	$2\overline{F_1 b_0 b_1}$	~~7.9537e-004~~	$2\overline{F_2 b_0 b_1}$	-1.3246
$2\overline{b_0 b_3}$	~~7.2465e-005~~	$2\overline{F_1 b_0 b_3}$	~~4.0882e-004~~	$2\overline{F_2 b_0 b_3}$	0.5353
$2\overline{b_0 b_4}$	-0.0316	$2\overline{F_1 b_0 b_4}$	-0.1038	$2\overline{F_2 b_0 b_4}$	~~6.5231e-005~~
$2\overline{b_1 b_3}$	-0.0480	$2\overline{F_1 b_1 b_3}$	1.0167	$2\overline{F_2 b_1 b_3}$	~~6.3873e-004~~
$2\overline{b_1 b_4}$	~~1.7632e-004~~	$2\overline{F_1 b_1 b_4}$	~~5.6206e-004~~	$2\overline{F_2 b_1 b_4}$	0.6139
$2\overline{b_3 b_4}$	~~3.4609e-004~~	$2\overline{F_1 b_3 b_4}$	~~6.2843e-005~~	$2\overline{F_2 b_3 b_4}$	-0.6508

Update equation for Nm (other than Navg)

1. The carrier rate equation is multiplied by the corresponding lateral distribution

$$F_m.\frac{\partial N}{\partial t} = F_m.\left(D\frac{\partial^2 N}{\partial x^2} + \frac{J}{ed} - R(N) - g(N)\frac{I}{\hbar\omega}\right)$$

2. The cross-sectional averaging is performed

$$\frac{1}{2}\frac{\partial N_m}{\partial t} = -D\frac{1}{2}\left(\frac{2\pi m}{W}\right)^2 N_m - \frac{1}{wd}\iint F_m.\left(R(N) - g(N)\frac{I}{\hbar\omega}\right)dx.dy$$

3. An update equation is obtained whose coefficients are dependent on the overlap integrals

Modified nonlinear propagation equation

The propagation of a wave envelop →

$$\frac{\partial A}{\partial z} = -\beta_1 \frac{\partial A}{\partial t} - \frac{i}{2}\beta_2 \frac{\partial^2 A}{\partial t^2} + \frac{1}{6}\beta_3 \frac{\partial^3 A}{\partial t^3} + \cdots + i\Delta\beta A$$

$$\frac{\partial A}{\partial z} \approx -\beta_1 \frac{\partial A}{\partial t} + (\Delta\beta'' - i\Delta\beta')A$$

Following the approximation of the first order perturbation →

$$\Delta\beta_n'' = \frac{1}{2}\frac{\iint g(N) b_n^2(x,y)dx.dy}{\iint b_n^2(x,y)dx.dy}$$

$$\Delta\beta_n'' = \frac{aN_{th}\Gamma_y}{2}\{\Gamma_{x,n}(N'_{avg} - 1) + \eta_{1,n}N'_1 + \eta_{2,n}N'_2 + \cdots \eta_{m,n}N'_m\}$$

where $\eta_{m,n}$ is the overlapping coefficient between mode n and carrier distribution m

$$\frac{\partial P_n}{\partial z} + \frac{1}{v_g}\frac{\partial P_n}{\partial t} = \frac{aN_{th}\Gamma_y}{2}\{\Gamma_{x,n}(N'_{avg} - 1) + \eta_{1,n}N'_1 + \eta_{2,n}N'_2 + \cdots \eta_{m,n}N'_m\} \cdot P_n - \alpha_{loss,n}P_n$$

$$\frac{\partial \phi_n}{\partial z} + \frac{1}{v_g}\frac{\partial \phi_n}{\partial t} = -\alpha_{fact}\frac{aN_{th}\Gamma_y}{2}\{\Gamma_{x,n}(N'_{avg} - 1) + \eta_{1,n}N'_1 + \eta_{2,n}N'_2 + \cdots \eta_{m,n}N'_m\}$$

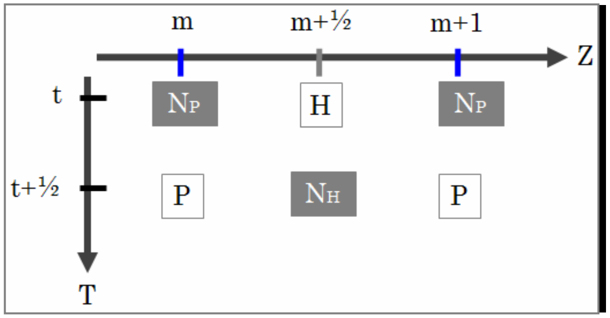
We only consider pulses wider than 14 ps

The wave equation should be modified to include SHB and CH if shorter pulses are to be examined

Solving the system of equations by artificial interleaving

$$\frac{\partial P_n}{\partial z} + \frac{1}{v_g}\frac{\partial P_n}{\partial t} = \frac{aN_{th}\Gamma_y}{2}\{\Gamma_{x,n}(N'_{avg} - 1) + \eta_{1,n}N'_1 + \eta_{2,n}N'_2 + \cdots \eta_{m,n}N'_m\} \cdot P_n - \alpha_{loss,n}P_n$$

$$\frac{\partial H_n}{\partial z} + \frac{1}{v_g}\frac{\partial P_n}{\partial t} = Q_n \cdot P_n$$



$$where\ \ Q_n = \frac{aN_{th}\Gamma_y}{2}\{\Gamma_{x,n}(N'_{avg} - 1) + \eta_{1,n}N'_1 + \eta_{2,n}N'_2 + \cdots \eta_{m,n}N'_m\} - \alpha_{loss,n}$$

$$\frac{1}{\Delta z}\left(H^t_{m+1/2} - H^t_{m-1/2}\right) + \frac{n_g}{c\Delta t}\left(P^{t+1/2}_m - P^{t-1/2}_m\right) = \frac{1}{2}Q^t_m \cdot \left(P^{t+1/2}_m + P^{t-1/2}_m\right)$$

Before Program Run Time

1. Solve the steady state carrier rate equation

    for a give injected current density

2. Find the corresponding value of the core effective index

    for a given alpha factor

3. Find the modes supported by the active MMI

    by solving the Eigen value problem

4. Find the coefficients of the excited modes

    by matching the supported modes to the profile of the exciting input

5. Formulate the code to include N number of modes and M number of carrier densities

    3 to 4 modes and 4 to 5 carrier profiles

6. Calculate all the coefficients used in the update equations

During Program Run Time

First Set of interleaved variables

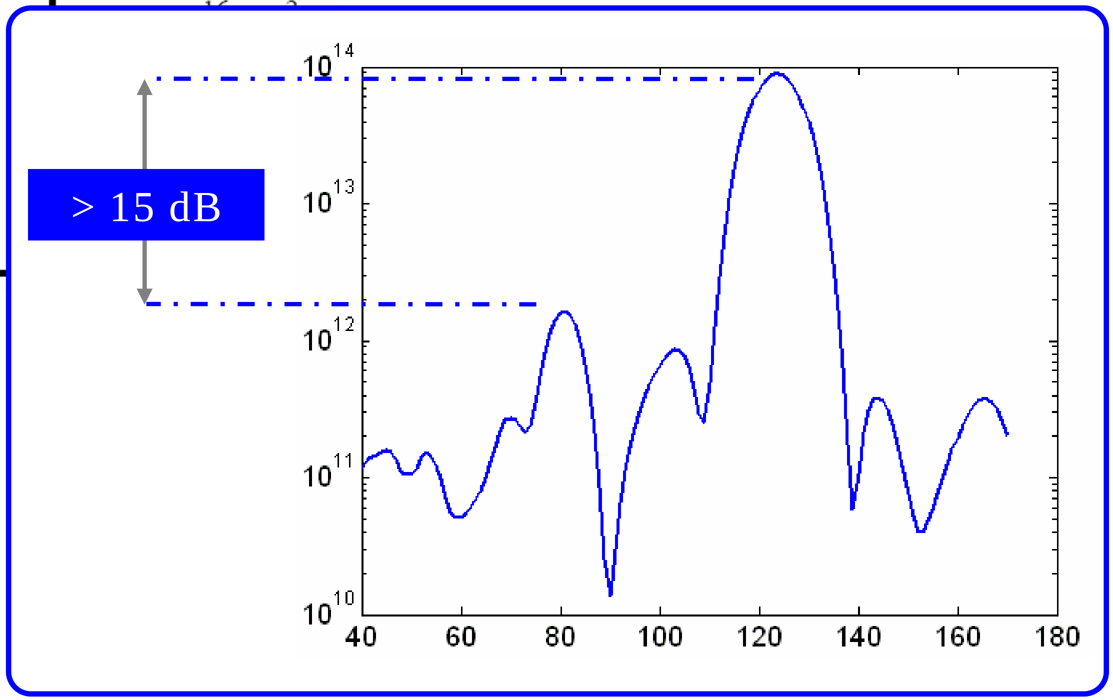
1. Updating the average carrier density
2. Updating the coefficients of the extra carrier density profiles
3. Updating the modal power coefficients
4. Updating the modal phase coefficient

Second Set of interleaved

1. Updating the average carrier density
2. Updating the coefficients of the extra carrier density profiles
3. Updating the modal power coefficients
4. Updating the modal phase coefficient

Simulation parameters

Parameter	Value
Effective index (core)	3.266
Effective index (cladding)	3.229
Propagation loss	20 cm^{-1}
Confinement factor	0.5
Thickness of active region	0.2 μm
Carrier density at transparency	0.8×10^{18} cm^{-3}
Differential gain	
Anti-guiding factor	
Self-saturation coefficient	
Unimolecular recombination coeff.	
Bimolecular recombination coeff.	
Auger recombination coeff.	



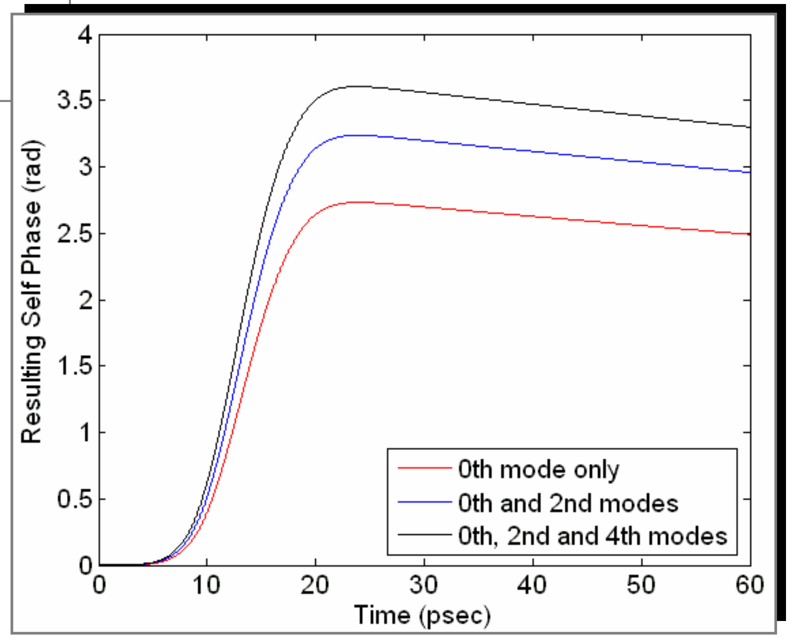
Self phase modulation in 1x1 active MMI

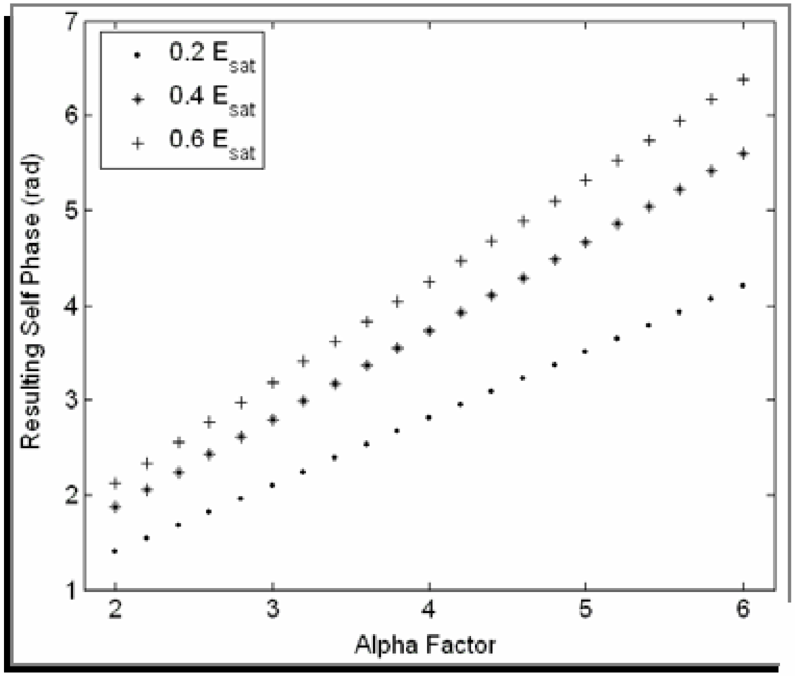
Input Gaussian un-chirped pulse of 15 ps FWHM

Injected current density 4.5 kA/cm2

MMI dimensions : 10 um x 900 um and 2 um feeding port

5 modes are supported and only three are excited

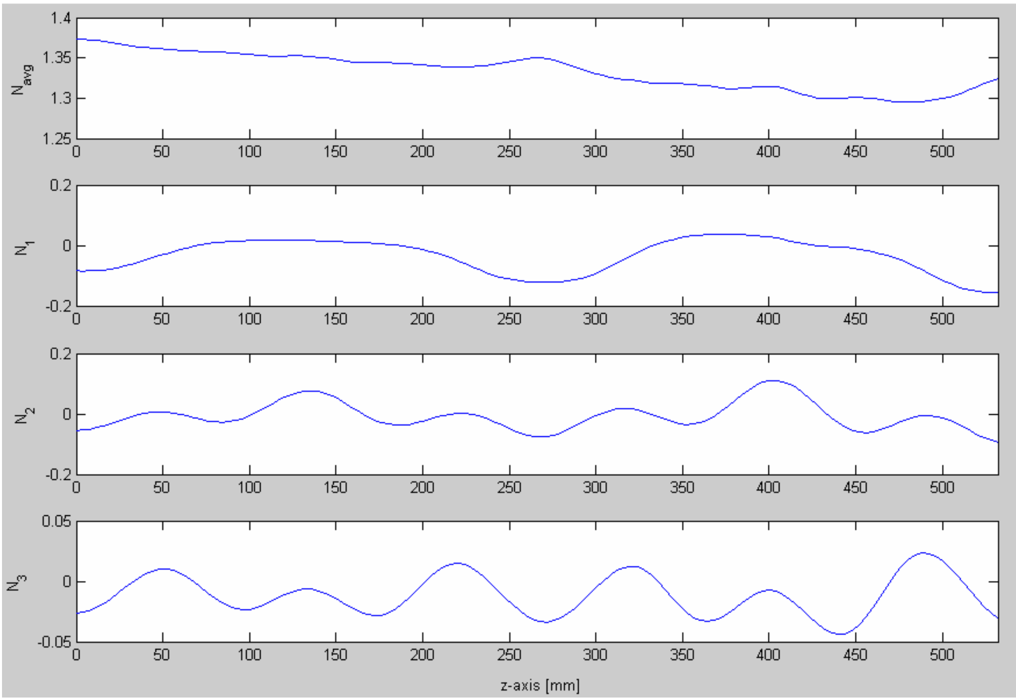


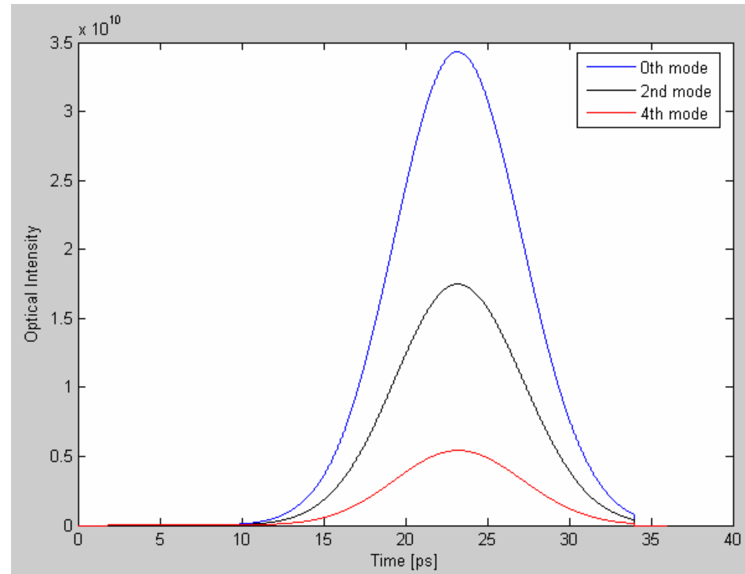


$$E_{sat} = \hbar\omega\, wd / a\Gamma_y$$

Mode	n_{eff}	n_g	C_j	$\eta_{1,j}$	$\zeta_{1,j}$
0th	3.2680	3.2695	0.759	-0.417	0.486
2nd	3.2621	3.2751	-0.543	0.103	0.587
4th	3.2507	3.2835	0.308	0.062	0.488

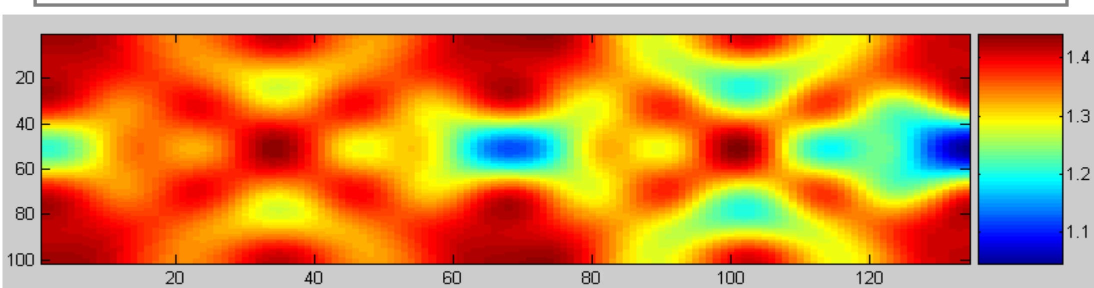
Carrier density distribution in a 1x1 active MMI





Optical modes at the MMI output

The total carrier density normalized by $N_{threshold}$



Pulse propagation with time in a 2x2 active MMI (1)

Input Gaussian un-chirped pulse of 15 ps FWHM

Injected current density 4.5 kA/cm2

MMI width & length are 10 & 720 um respectively

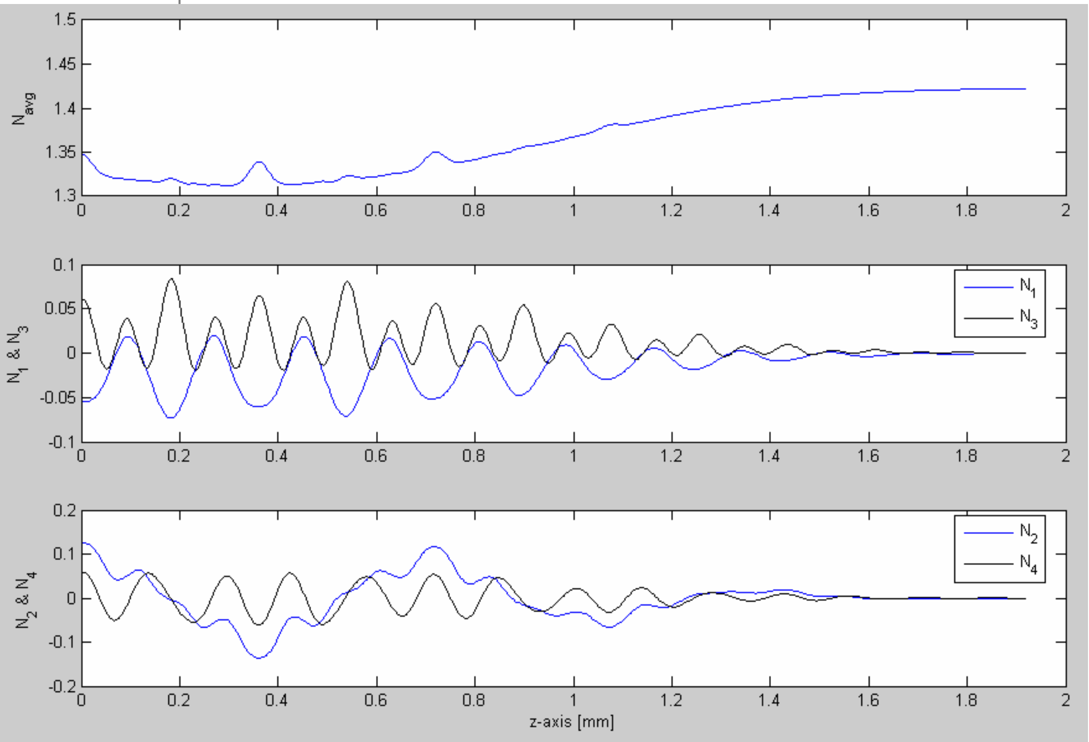
Width of feeding port is 2 um

4 modes are excited

5 carrier distributions including average

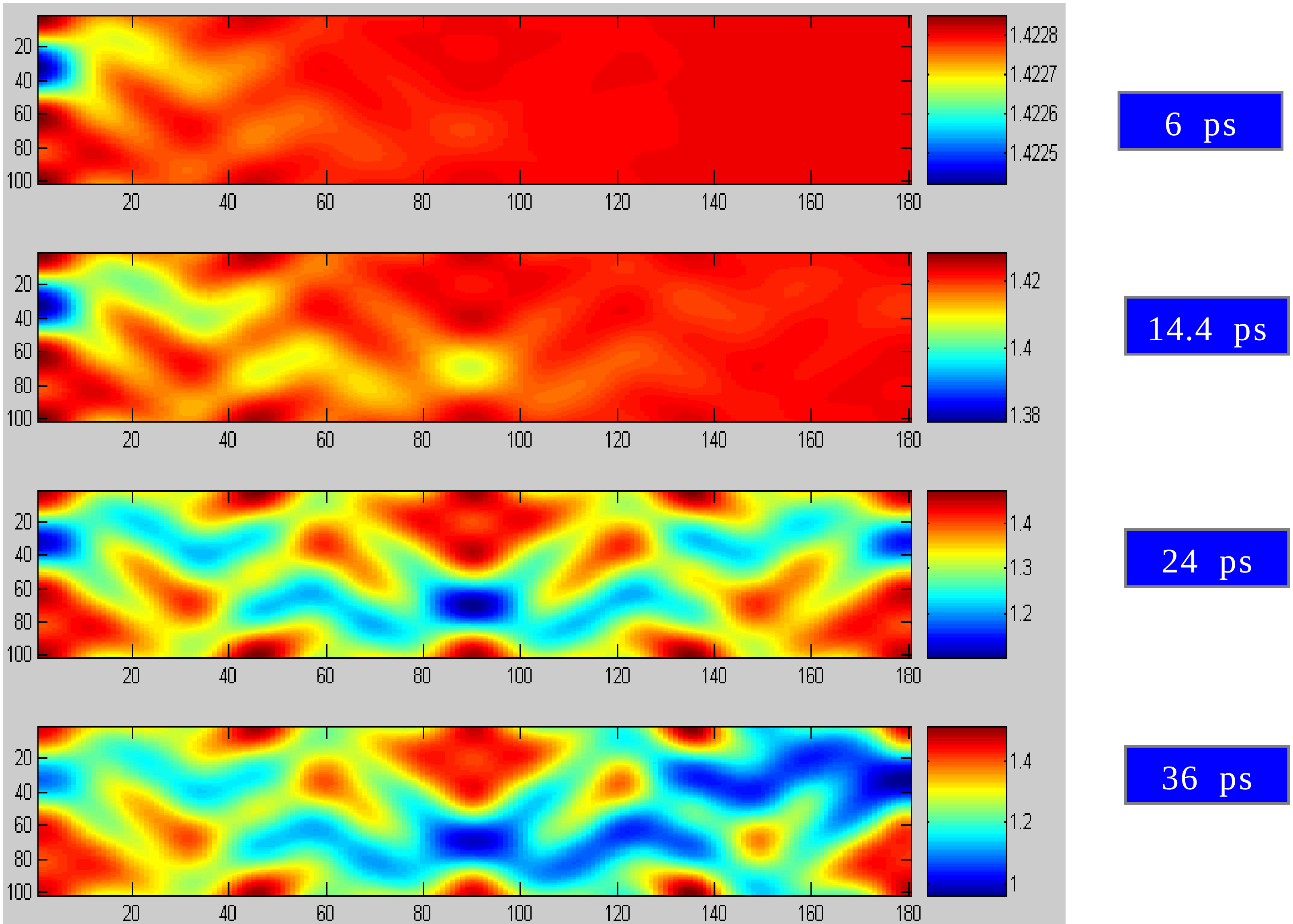
$\Delta t = 1.2$ fs

$\Delta z = 4$ um



$$N(x,z) = N_{avg}(z,t) + N_1(z,t)\cos\left(\frac{2\pi x}{W}\right) + N_2(z,t)\sin\left(\frac{2\pi x}{W}\right) + N_3(z,t)\cos\left(\frac{4\pi x}{W}\right) + N_4(z,t)\sin\left(\frac{4\pi x}{W}\right)$$

Pulse propagation with time in a 2x2 active MMI (2)



Summary and outlook

Optical pulse propagation in narrow active MMI is modeled and simulated.

A set of adapted nonlinear wave equations coupled with approx. carrier densities are derived then numerically solved.

The numerical solution is based on artificial interleaving of optical fields and carrier coefficients; in which they are solved by the FDTD method.

Self phase modulation in single-input single-output active MMI are calculated with the developed code.

XGM and XPM in 2x2 active MMI's are currently under development .