Electrooptic Matched Filter Controlled by Independent Voltages Applied to Multiple Sets of Electrodes

Contents

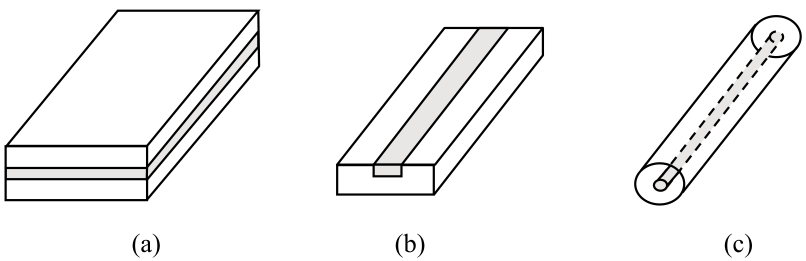
I. Introduction

- Optical filters - essential components in a wavelength-division multiplexed (WDM) optical networks
- Electrooptic tunable filters (EOTFs) - a good solution for sub-microsecond tunability through TE-TM mode coupling
- Conventional EOTF - a Mach-Zehnder interferometer structure, phase-matched polarization conversion, and polarization beam splitter
- Electrooptic matched filter (EMF) is a new type of EOTF providing wide spectral tuning range and rapid tuning
- EMF - designed for operation in the 1550 nm wavelength regime for 100 GHz (0.8 nm) channel spacing corresponding to the ITU–T grid

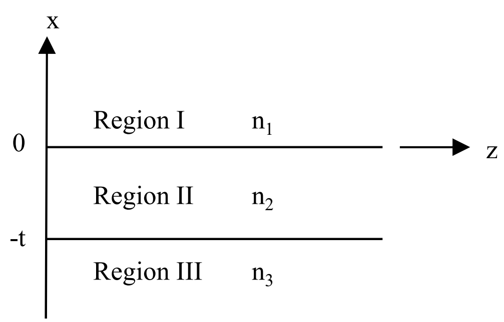
II. Mode Coupling in Optical Waveguide

A. TE and TM Modes in Slab Dielectric Waveguide

- Optical waveguide



- The step-index planar waveguide is the simplest structure for discussing fundamental properties of guided modes



Wave Equation in Slab Waveguide

- The allowed modes of this waveguide are obtained from the wave equation given by

$$\nabla^2 \mathbf{E}(\mathbf{r}) + k_0^2 n^2(\mathbf{r}) \mathbf{E}(\mathbf{r}) = 0$$

- The solutions are subject to the boundary conditions: tangential components of E and H are continuous at the interfaces x = 0 and –t

- Assuming an isotropic and lossless medium in the waveguide, Maxwell's equations written by

$$\nabla \times \mathbf{H} = -\varepsilon_0 n^2 \frac{\partial \mathbf{E}}{\partial t} \quad \text{and} \quad \nabla \times \mathbf{E} = -\mu_0 \frac{\partial \mathbf{H}}{\partial t}$$

yields two orthogonal modes

TE and TM Modes

	Transverse electric (TE) mode	Transverse magnetic (TM) mode
Wave equation	$\frac{\partial^2}{\partial x^2}E_y + (k_0^2n^2 - \beta^2)E_y = 0$	$\frac{\partial^2}{\partial x^2}H_y + (k_0^2n^2 - \beta^2)H_y = 0$
Maxwell's equations	$H_y = -\frac{\beta}{\omega\mu_0}E_y$ $H_z = -\frac{1}{j\omega\mu_0}\frac{\partial E_y}{\partial x}$	$E_x = \frac{\beta}{\omega\varepsilon_0 n^2}H_y$ $E_z = \frac{1}{j\omega\varepsilon_0 n^2}\frac{\partial H_y}{\partial x}$
TE/TM Mode field solution in each layer	$E_y = Ce^{-qx},\ x > 0$ $E_y = C[\cos(hx) - \frac{q}{h}\sin(hx)],\ -t \le x \le 0$ $E_y = C[\cos(ht) + \frac{q}{h}\sin(ht)]e^{p(x+t)},\ x < -t$	$H_y = -C'\frac{h}{q}e^{-qx},\ x > 0$ $H_y = C'[-\frac{h}{q}\cos(hx) + \sin(hx)],\ -t \le x \le 0$ $H_y = -C'[\frac{h}{q}\cos(ht) + \sin(ht)]e^{p(x+t)},\ x < -t$
Eigenvalue equation	$\tan(ht) = \frac{p+q}{h - \frac{pq}{h}}$	$\tan(ht) = \frac{\frac{n_2^2}{n_3^2}p + \frac{n_2^2}{n_1^2}q}{h - \left(\frac{n_2^2}{n_1 n_3}\right)^2\frac{pq}{h}}$

where $q = \sqrt{\beta^2 - k_0^2n_1^2},\ h = \sqrt{k_0^2n_2^2 - \beta^2},\ p = \sqrt{\beta^2 - k_0^2n_3^2}$ and $k_0 n_3 < \beta < k_0 n_2$

II. Mode Coupling in Optical Waveguide

B. TE/TM Polarization Converter

› Coupled Mode Theory in Optical Waveguide

In an isotropic charge-free medium, eigen modes satisfy the wave equation in the form

$$\nabla^2 \mathbf{E}(\mathbf{r}, t) = \mu\varepsilon(\mathbf{r}) \frac{\partial^2 \mathbf{E}(\mathbf{r}, t)}{\partial t^2}$$

using

$$\boldsymbol{\nabla} \cdot (\boldsymbol{\varepsilon E}) = \mathbf{0}$$

$$\boldsymbol{\nabla} \times \boldsymbol{\nabla} \times \boldsymbol{E} \equiv \boldsymbol{\nabla}(\boldsymbol{\nabla} \cdot \boldsymbol{E}) - \boldsymbol{\nabla}^2 \boldsymbol{E}$$

$$\boldsymbol{\nabla} \times \boldsymbol{H} = -\boldsymbol{\varepsilon}_0 \boldsymbol{n}^2 \frac{\partial \boldsymbol{E}}{\partial \boldsymbol{t}}$$

Curl and substitute

$$\boldsymbol{\nabla} \times \boldsymbol{E} = -\boldsymbol{\mu}_0 \frac{\partial \boldsymbol{H}}{\partial \boldsymbol{t}}$$

Coupled Mode Theory Continued…

- With the electric polarization of the medium $\mathbf{P}(\mathbf{r}, t)$

$$\nabla^2 \mathbf{E}(\mathbf{r}, t) = \mu\varepsilon_0 \frac{\partial^2 \mathbf{E}(\mathbf{r}, t)}{\partial t^2} + \mu \frac{\partial^2}{\partial t^2} \mathbf{P}(\mathbf{r}, t)$$

where $\mathbf{P}(\mathbf{r}, t) = [\varepsilon(\mathbf{r}) - \varepsilon_{\mathbf{0}}]\mathbf{E}(\mathbf{r}, t)$, $\varepsilon(\mathbf{r})$:Medium dielectric constant

- If the deformation in the waveguide is taken into account, the induced perturbation in the polarization results in

$$\nabla^2 \mathbf{E}(\mathbf{r}, t) = \mu \frac{\partial^2}{\partial t^2} [\varepsilon(\mathbf{r})\mathbf{E}(\mathbf{r}, t) + \mathbf{P}_{pert}(\mathbf{r}, t)]$$

- Assuming only the TE mode

$$\nabla^2 E_y(\mathbf{r}, t) - \mu \frac{\partial^2}{\partial t^2} \varepsilon(\mathbf{r}) E_y(\mathbf{r}, t) = \mu \frac{\partial^2}{\partial t^2} [P_{pert}(\mathbf{r}, t)]_y$$

- The following equation is derived after some calculation and used to consider TE and TM mode interaction.

$$\frac{dA_s^-}{dz} e^{j(\omega t + \beta_s z)} - \frac{dA_s^+}{dz} e^{j(\omega t - \beta_s z)} - c.c. = -\frac{j}{2\omega} \frac{\partial^2}{\partial t^2} \int_{-\infty}^{\infty} [P_{pert}(\mathbf{r}, t)]_y \, E_y^s(x) dx$$

Electrooptic Effect in a Uniaxial Crystal

- An electrooptic material undergoes the change in the refractive index induced by applied electric field linearly (Pockels effect) or quadratically (Kerr effect) and this phenomenon is called the electrooptic effect

- The electric flux density $\mathbf{D}$ in an anisotropic dielectric media is written by with dielectric constants and electric fields

$$
\begin{aligned}
D_x &= \varepsilon_{11}E_x + \varepsilon_{12}E_y + \varepsilon_{13}E_z \\
D_y &= \varepsilon_{21}E_x + \varepsilon_{22}E_y + \varepsilon_{23}E_z \\
D_z &= \varepsilon_{31}E_x + \varepsilon_{32}E_y + \varepsilon_{33}E_z
\end{aligned}
$$

- If the coordinate system in a crystal structure is chosen to vanish off-diagonal elements, the axes in this coordinate system are defined as principal axes and a 3×3 electric permeability tensor can be expressed as

$$
[\varepsilon] = \begin{bmatrix} \varepsilon_{11} & 0 & 0 \\ 0 & \varepsilon_{22} & 0 \\ 0 & 0 & \varepsilon_{33} \end{bmatrix}
$$

Index Ellipsoid

- Recalling the electric energy density stored in a crystal
  $w_e = \frac{1}{2}\mathbf{E}\cdot\mathbf{D}$ and $\mathbf{D} = \varepsilon_0[\varepsilon]\mathbf{E}$

  w_e takes a form of

$$\boldsymbol{w_e = \frac{1}{2}\left(\frac{D_x^2}{\varepsilon_{11}} + \frac{D_y^2}{\varepsilon_{22}} + \frac{D_z^2}{\varepsilon_{33}}\right)}$$

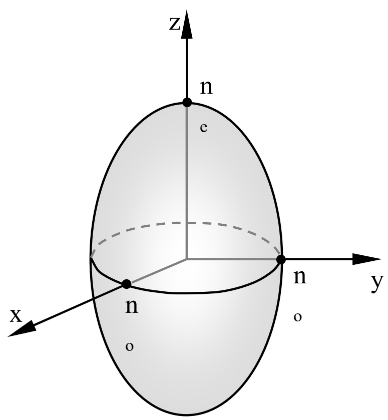
- Replacing $D_i/\sqrt{2\varepsilon_0 w_e}$ where i = x, y, z with X, Y, and Z we have the index ellipsoid described by

$$\boldsymbol{\frac{X^2}{n_x^2} + \frac{Y^2}{n_y^2} + \frac{Z^2}{n_z^2} = 1}$$

  where $n_x = \sqrt{\varepsilon_{11}/\varepsilon_0}$, $n_y = \sqrt{\varepsilon_{22}/\varepsilon_0}$, and $n_z = \sqrt{\varepsilon_{33}/\varepsilon_0}$ are principal refractive indices.

Index Ellipsoid of Uniaxial Crystal

- In the uniaxial crystal, it is noticed that $n_x = n_y = n_o$ and $n_z = n_e$ where n_o and n_e are called the ordinary and extraordinary indices, respectively and the z axis is called the optic axis



Electrooptic Tensor

- The presence of electric field applied in an arbitrary direction to a crystal leads to a linear change in the coefficient $1/n_i^2$ according to

$$\Delta\left(\frac{1}{n^2}\right)_i = \sum_j r_{ij}E_j \qquad i = 1,\ \ldots,\ 6,\ \ j = 1,\ 2,\ 3$$

In a matrix form $\longrightarrow$

$$\begin{vmatrix} \Delta(1/n^2)_1 \\ \Delta(1/n^2)_2 \\ \Delta(1/n^2)_3 \\ \Delta(1/n^2)_4 \\ \Delta(1/n^2)_5 \\ \Delta(1/n^2)_6 \end{vmatrix} = \begin{vmatrix} r_{11} & r_{12} & r_{13} \\ r_{21} & r_{22} & r_{23} \\ r_{31} & r_{32} & r_{33} \\ r_{41} & r_{42} & r_{43} \\ r_{51} & r_{52} & r_{53} \\ r_{61} & r_{62} & r_{63} \end{vmatrix} \begin{vmatrix} E_1 \\ E_2 \\ E_3 \end{vmatrix}$$

- The 6×3 electrooptic tensor composed of the electrooptic coefficient r_{ij} has a different form for noncentroelectric crystals.
  The electrooptic tensor of LiNbO3 - a uniaxial material of the 3m trigonal crystal class:

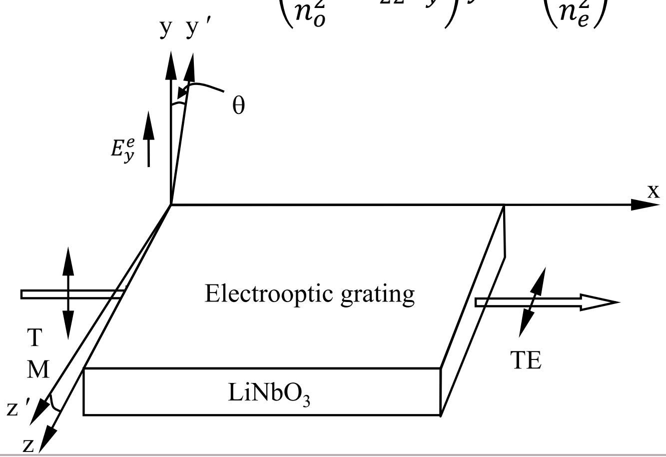
$$\begin{bmatrix} 0 & -r_{22} & r_{13} \\ 0 & r_{22} & r_{13} \\ 0 & 0 & r_{33} \\ 0 & r_{51} & 0 \\ r_{51} & 0 & 0 \\ -r_{22} & 0 & 0 \end{bmatrix}$$

Axis transformation

- The new index ellipsoid in the applied electric field is described by

$$\left(\frac{1}{n^2}\right)_1' x^2 + \left(\frac{1}{n^2}\right)_2' y^2 + \left(\frac{1}{n^2}\right)_3' z^2 + 2\left(\frac{1}{n^2}\right)_4' yz + 2\left(\frac{1}{n^2}\right)_5' xz + 2\left(\frac{1}{n^2}\right)_6' xy = 1$$

- For various electric field directions in y-cut, x-propagating LiNbO3, the electric field E_y^e applied uniformly along y axis is considered. The index ellipsoid becomes $\left(\frac{1}{n_o^2} + r_{22}E_y^e\right)y^2 + \left(\frac{1}{n_e^2}\right)z^2 + 2r_{51}E_y^e yz = 1$



Axis transformation Continued…

- The existence of the mixed yz term implies the index ellipsoid is rotated about x axis and x, y, and z are no longer the principal axes. The perturbed index ellipsoid in new x′y′ plane is expressed by

$$\frac{y'^2}{n_{y'}^2} + \frac{z'^2}{n_{z'}^2} = 1$$

where

$$\begin{bmatrix} x \\ y' \\ z' \end{bmatrix} = [T]\begin{bmatrix} x \\ y \\ z \end{bmatrix}, \quad [T] = \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos\theta & -\sin\theta \\ 0 & \sin\theta & \cos\theta \end{bmatrix}$$

- Since practically $n_{x'} \simeq n_o$, $n_{y'} \simeq n_o$, and $n_{z'} \simeq n_e$ for LiNbO3

$$[\varepsilon'] = \begin{bmatrix} n_{x'}^2 & 0 & 0 \\ 0 & n_{y'}^2 & 0 \\ 0 & 0 & n_{z'}^2 \end{bmatrix} \simeq \begin{bmatrix} n_o^2 & 0 & 0 \\ 0 & n_o^2 & 0 \\ 0 & 0 & n_e^2 \end{bmatrix} \xrightarrow{[\varepsilon] = [T]^T[\varepsilon'][T]} [\varepsilon] = \begin{bmatrix} \varepsilon_{11} & 0 & 0 \\ 0 & \varepsilon_{22} & \delta\varepsilon_{23} \\ 0 & \delta\varepsilon_{23} & \varepsilon_{33} \end{bmatrix}$$

Axis transformation Continued…

- Considering the TM polarized optical wave propagates in a crystal and off-diagonal elements in the permeability tensor are induced by electric field E_y^e, the polarization $\delta\mathbf{P} = \varepsilon_{\mathbf{0}}([\varepsilon'] - [\varepsilon])\mathbf{E}$ is described by

$$\begin{bmatrix} \delta P_x \\ \delta P_y \\ \delta P_z \end{bmatrix} = \varepsilon_0 \begin{bmatrix} 0 & 0 & 0 \\ 0 & 0 & -\delta\varepsilon_{23} \\ 0 & -\delta\varepsilon_{23} & 0 \end{bmatrix} \begin{bmatrix} 0 \\ E_y^\omega \\ 0 \end{bmatrix}$$

- Perturbation in the permeability tensor induced by electric field E_y^e gives rise to the perturbation in the optical wave E_y^ω written by .

$$\delta P_z = -\varepsilon_0 \delta\varepsilon_{23} E_y^\omega$$

TE↔TM Mode Converter

- The TE↔TM mode conversion between two codirectional and orthogonal modes is described by the coupled mode equations

$$\frac{dA_m}{dx} = -i\kappa B_m e^{-i\Delta\beta x}$$
$$\frac{dB_m}{dx} = -i\kappa A_m e^{-i\Delta\beta x}$$

where A_m and B_m are complex amplitudes of the two coupled optical waves

$$\Delta\beta \equiv \beta_{TM} - \beta_{TE}$$

$$\kappa = \frac{1}{2}(n_e n_o)^{3/2} k_0 r_{51} E_y^e$$

Solution of Coupled Mode Equations

- Assuming the boundary conditions

$$A_m(x=0)=0$$
$$B_m(x=0)=B_0$$

the solutions are obtained as

$$A_m(x) = -B_0 e^{-\delta x}\frac{\kappa}{\sqrt{\kappa^2+\delta^2}}\sin\left(\sqrt{\kappa^2+\delta^2}x\right)$$
$$B_m(x) = B_0 e^{-\delta x}\left[\cos\left(\sqrt{\kappa^2+\delta^2}x\right) - \frac{i\delta}{\sqrt{\kappa^2+\delta^2}}\sin\left(\sqrt{\kappa^2+\delta^2}x\right)\right]$$

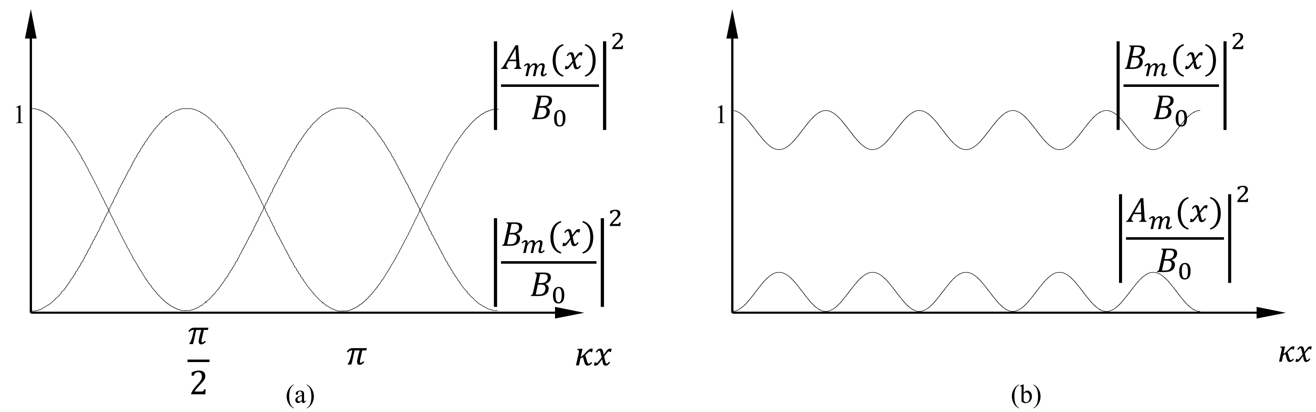
where $\delta \equiv \frac{1}{2}(\beta_{TM}-\beta_{TE})$

- When the two modes are phase matched, we have the simpler solution

$$A_m = -B_0\sin(\kappa x)$$
$$B_m = B_0\cos(\kappa x)$$

Power conversion over coupling length

- The plot of the normalized powers $|A_m(x)/B_0|^2$ and $|B_m(x)/B_0|^2$

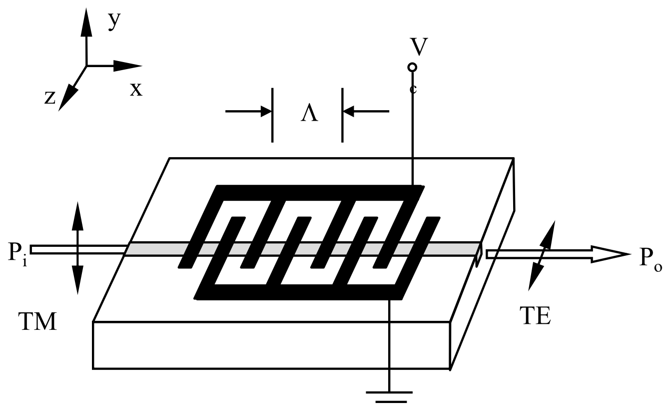


- The shortest coupling length L for full power transfer is denoted by

$$L = \frac{\pi}{2\kappa}$$

Power conversion over coupling length Continued…

- Full power transfer requires phase-matching condition that $\beta_{TM} = \beta_{TE}$ in the uniform waveguide structure and $\beta_{TM} - \beta_{TE} = 2\pi/\Lambda$ in the periodic structure



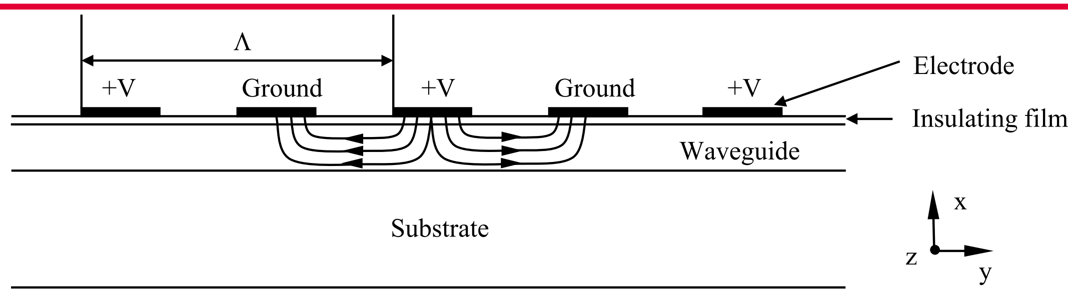
- The periodicity of the structure compensates the difference between two propagation constants
- Assuming the phase-matching condition at a certain wavelength, the polarization converter behaves as a wavelength filter and the optical bandwidth of TE↔TM conversion becomes

$$\Delta\lambda_{FWHM} \approx 0.8\left(\frac{\Lambda}{L}\right)\lambda$$

III. Design of Electrooptic Matched Filter

A. The Principal Characteristics of EMF

- The x component of electric field provides TE↔TM mode conversion induced by $\delta\varepsilon_{23}$ perturbation in the permeability tensor via the electrooptic coefficient r_{51}



- The mode conversion is a wavelength selective process. The most efficient wavelength λ_0 is found by the phase-matching condition as

$$\lambda_0 = \Lambda|n_{TM} - n_{TE}|$$

Λ : the period of interdigital electrodes

n_{TM}, n_{TE}: the effective refractive indices of the TM and TE modes

Principal Characteristics of EMF Continued…

- Wavelength selection is achieved if the first order phase-matching condition $\Delta = 0$ is satisfied, where the phase mismatch constant Δ is

$$\Delta = \frac{2\pi\nu(n_{TM} - n_{TE})}{c} \pm \frac{2\pi}{\Lambda}$$

- Hence, the tuning mechanism can be described by applying the voltage to the electrodes to nullify Δ at any desired frequency

- The sidelobe levels are suppressed to below –10 dB by applying a raised cosine apodizing function

$$\kappa(y) = \kappa_0 + 0.5\kappa_0 \cos\left[2\pi\left(\frac{y}{L} - 0.5\right)\right]$$

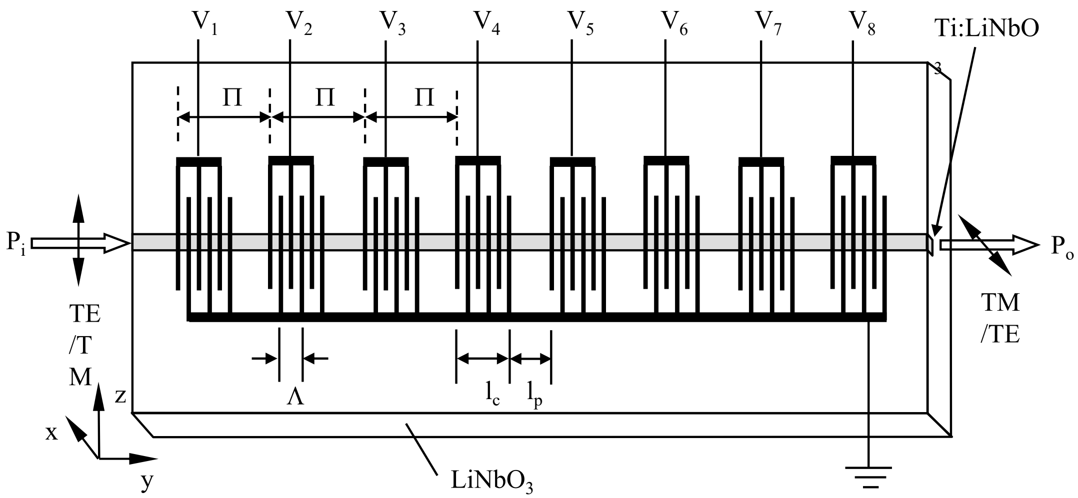
III. Design of Electrooptic Matched Filter

B. The EMF Structure for Two Sidebands

- The array of electrode sets is formed on the waveguide which is fabricated on an x-cut y-propagating LiNbO3 substrate by Ti diffusion

- The EMF is composed of 8 sets of interdigital electrodes to tune 5 wavelength channels according to the relation $N = P/2 + 1$
  where N : the number of selectable channels,
  P : the number of electrode sets

EMF Structure for Two Sidebands Continued…



$\Lambda = 21\ \mu m$: spatial period of interdigital electrodes

$\Pi = 200 \cdot \Lambda$: period of electrode sets

$l_c = (179 + 3/4) \cdot \Lambda$: length of single mode conversion region

Coupling Strength Distribution

- The ideal coupling strength distribution along the length of the electrode sets in the structure for two sidebands is

$$\kappa_j(y) = S(y)\cos(\Delta_j y), \quad j = 1,\ 2,\ 3, \cdots,\ N$$

$S(y)$: the apodization function

$$\Delta_j = \frac{2\pi\left|n_{1g} - n_{3g}\right|(\nu_j - \nu_0)}{c}$$

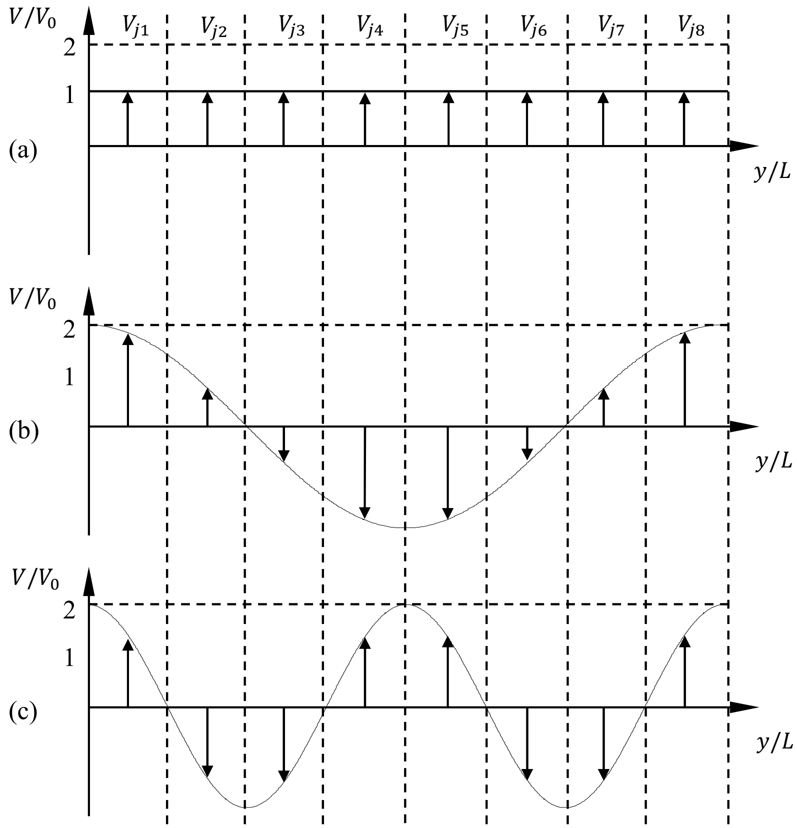
- The integral of coupling coefficient over the interaction length L is given by

$$\int_0^L \kappa dy = \frac{\pi}{2}$$

for a complete TE↔TM power conversion

Applied Voltages to Eight Sets of Electrodes

- In this research, V_0 is obtained experimentally to optimize the polarization conversion



The Ratio of V_{jp} to V_0 – Two Sidebands

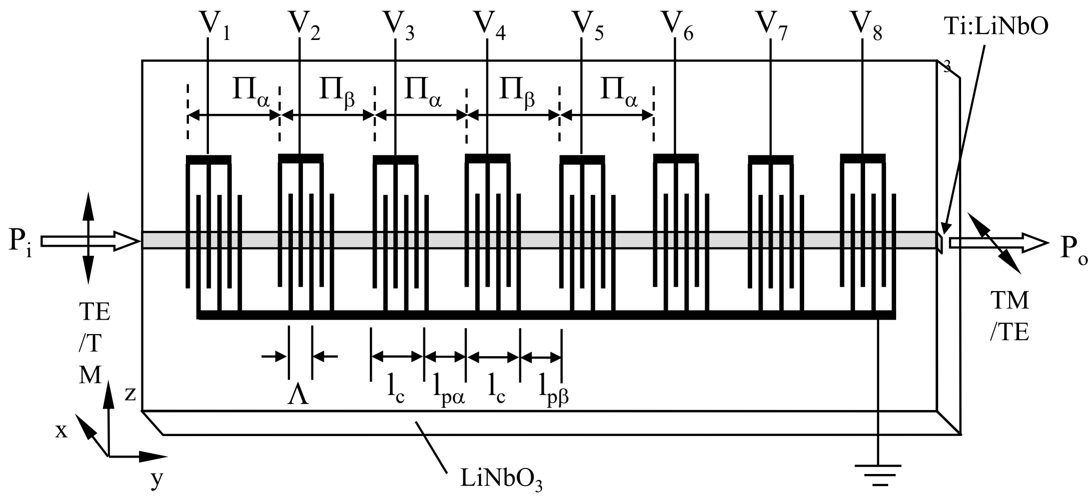
- The voltages for the raised cosine apodization are obtained by using equation

$$\kappa_j(y) = S(y)\cos(\Delta_j y)\left(1 + 0.5\cos\left[2\pi\left(\frac{y}{L} - 0.5\right)\right]\right)$$

j, channel		p, the number of electrode set							
		1	2	3	4	5	6	7	8
Without apodization	0	1	1	1	1	1	1	1	1
	±1	1.848	0.765	-0.765	-1.848	-1.848	-0.765	0.765	1.848
	±2	1.414	-1.414	-1.414	1.414	1.414	-1.414	-1.414	1.414
With raised cosine apodization	0	0.538	0.809	1.191	1.462	1.462	1.191	0.809	0.538
	±1	0.994	0.619	-0.912	-2.701	-2.701	-0.912	0.619	0.994
	±2	0.761	-1.144	-1.685	2.067	2.067	-1.685	-1.144	0.761

III. Design of Electrooptic Matched Filter

C. The EMF Structure for Single Sideband



$\Lambda = 21\ \mu m$: spatial period of interdigital electrodes

$\Pi_\alpha = (200 - 1/4)\Lambda$, $\Pi_\beta = (200 + 1/4)\Lambda$

$l_c = (179 + 3/4) \cdot \Lambda$: length of single mode conversion region

Coupling Strength Distribution

- The regions of Π_α and Π_β cause in-phase and quadrature coupling, respectively. The coupling coefficient is complex and is written by

$$\kappa_j(y) = S(y)e^{i\Delta_j y}$$

- For the in-phase and quadrature coupling, the coupling coefficient κ_j is written by

$$\kappa_j(y) = S(y)\cos(\Delta_j y), \quad j = \pm(2n-1)$$
$$\kappa_j(y) = iS(y)\sin(\Delta_j y), \quad j = \pm 2n$$

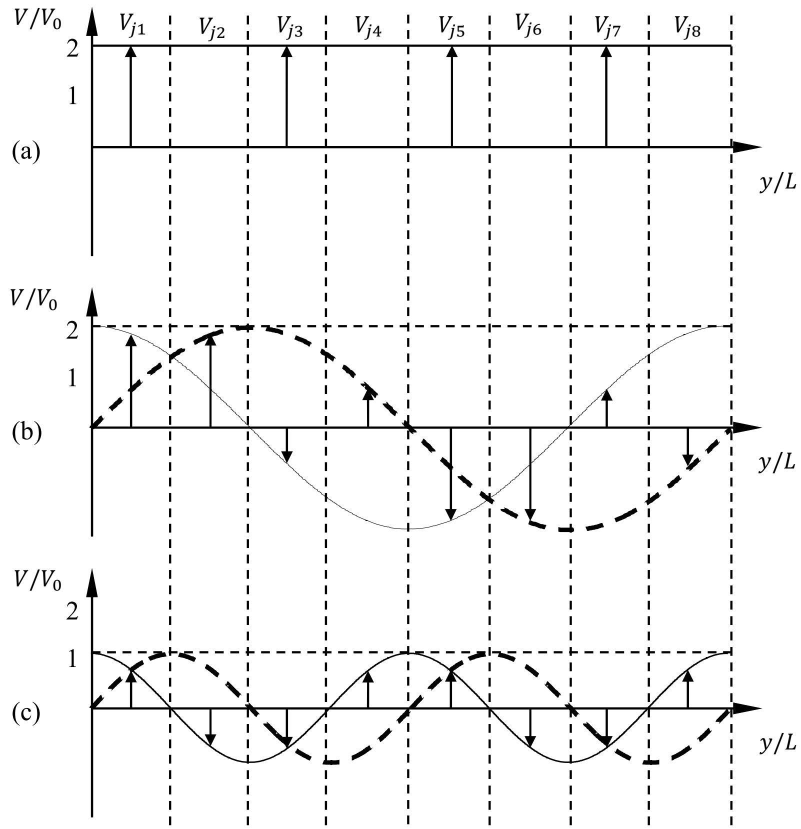
- The selected voltages for j'th frequency channel satisfy the relation

$$\int_0^L \kappa_j(y)\, e^{-i\Delta_k y} dy = \frac{\pi}{2}\delta_{jk}$$

with $\delta_{jk} = 1$ if $j = k$ and $\delta_{jk} = 0$ otherwise

Applied Voltages to Eight Sets of Electrodes

- Selection of voltages in the structure of a single sideband: (a) for $j = 0$ sideband, (b) for $j = 1$ sideband, (c) for $j = 2$ sideband.



The ratio of V_{jp} to V_0 – Single Sideband

j, channel		p, the number of electrode set							
		1	2	3	4	5	6	7	8
Without apodization	-2	0.707	-0.707	-0.707	0.707	0.707	-0.707	-0.707	0.707
	-1	1.848	-1.848	-0.765	-0.765	-1.848	1.848	0.765	0.765
	0	2	0	2	0	2	0	2	0
	1	1.848	1.848	-0.765	0.765	-1.848	-1.848	0.765	-0.765
	2	0.707	0.707	-0.707	-0.707	0.707	0.707	-0.707	-0.707
With raised cosine apodization	-2	0.380	-0.572	-0.842	1.034	1.034	-0.842	-0.572	0.380
	-1	0.994	-1.494	-0.912	-1.119	-2.701	2.201	0.619	0.412
	0	1.076	0	2.383	0	2.924	0	1.617	0
	1	0.994	1.494	-0.912	1.119	-2.701	-2.201	0.619	-0.412
	2	0.380	0.572	-0.842	-1.034	1.034	0.842	-0.572	-0.380

III. Design of Electrooptic Matched Filter

D. Matrix Formulation and Simulation Results

- The effect of polarization conversion in the j'th coupling region and of phase shift in the spacing between electrodes is written by

$$\mathbf{E_{j+1}} = \mathbf{M_j}\mathbf{E_j}$$

where $$\mathbf{E_j} = \begin{pmatrix} E_j^{TE} \\ E_j^{TM} \end{pmatrix}, \quad j = 1,\ 2,\ 3, \cdots,\ P$$

E_j^{TM}, E_j^{TE} : electric field amplitudes of two polarization modes just prior to the j'th coupling region

Matrix Formulation Continued…

- The 2×2 transfer matrix $\mathbf{M_j}$ is given by $\mathbf{M_j^C M^\Phi}$
- Here, the matrix $\mathbf{M^\Phi}$ describes the phase shift occurring at the propagation region between adjacent coupling regions, which is given by

$$\mathbf{M^\Phi} = \begin{bmatrix} e^{-i\frac{\varphi}{2}} & 0 \\ 0 & e^{i\frac{\varphi}{2}} \end{bmatrix}$$

where $\varphi = (\beta_1 - \beta_2)l_p$ $\beta_1 = 2\pi\nu n_{TE}/c$ $\beta_2 = 2\pi\nu n_{TM}/c$ $l_p = \Pi - l_c$

- The matrix $\mathbf{M_j^C}$ representing the effect of polarization conversion at the j'th coupling region is in general written by adapting the well known solution of the coupled mode equations

$$\mathbf{M_j^C} = \begin{bmatrix} a_c e^{-i(\beta_1 + \frac{\Delta}{2})l_c} & b_c e^{-i(\beta_1 + \frac{\Delta}{2})l_c} \\ -b_c^* e^{-i(\beta_2 - \frac{\Delta}{2})l_c} & a_c e^{-i(\beta_2 - \frac{\Delta}{2})l_c} \end{bmatrix}$$ where $$a_c = \cos(\sqrt{\kappa^2 + \delta^2} l_c) + i \frac{\delta}{\sqrt{\kappa^2 + \delta^2}}$$ $$b_c = -i \frac{\delta}{\sqrt{\kappa^2 + \delta^2}} \sin(\sqrt{\kappa^2 + \delta^2} l_c)$$

Conversion Matrix

› The EMF consists of the first coupling region and the $P-1$ pairs of alternating polarization conversion region and the spacing between them, so that the conversion matrix is given by

$$C = \left(\prod_{j=2}^{P} \mathbf{M}_{\mathbf{j}}^{\mathbf{C}} \mathbf{M}^{\boldsymbol{\Phi}} \right) \mathbf{M}_{1}^{\mathbf{C}}$$

› Assuming that the TE polarization mode is excited at the input of EMF and its amplitude is normalized to 1, the power coupling efficiency is written by

$$PCE = |C_{12}|^2$$

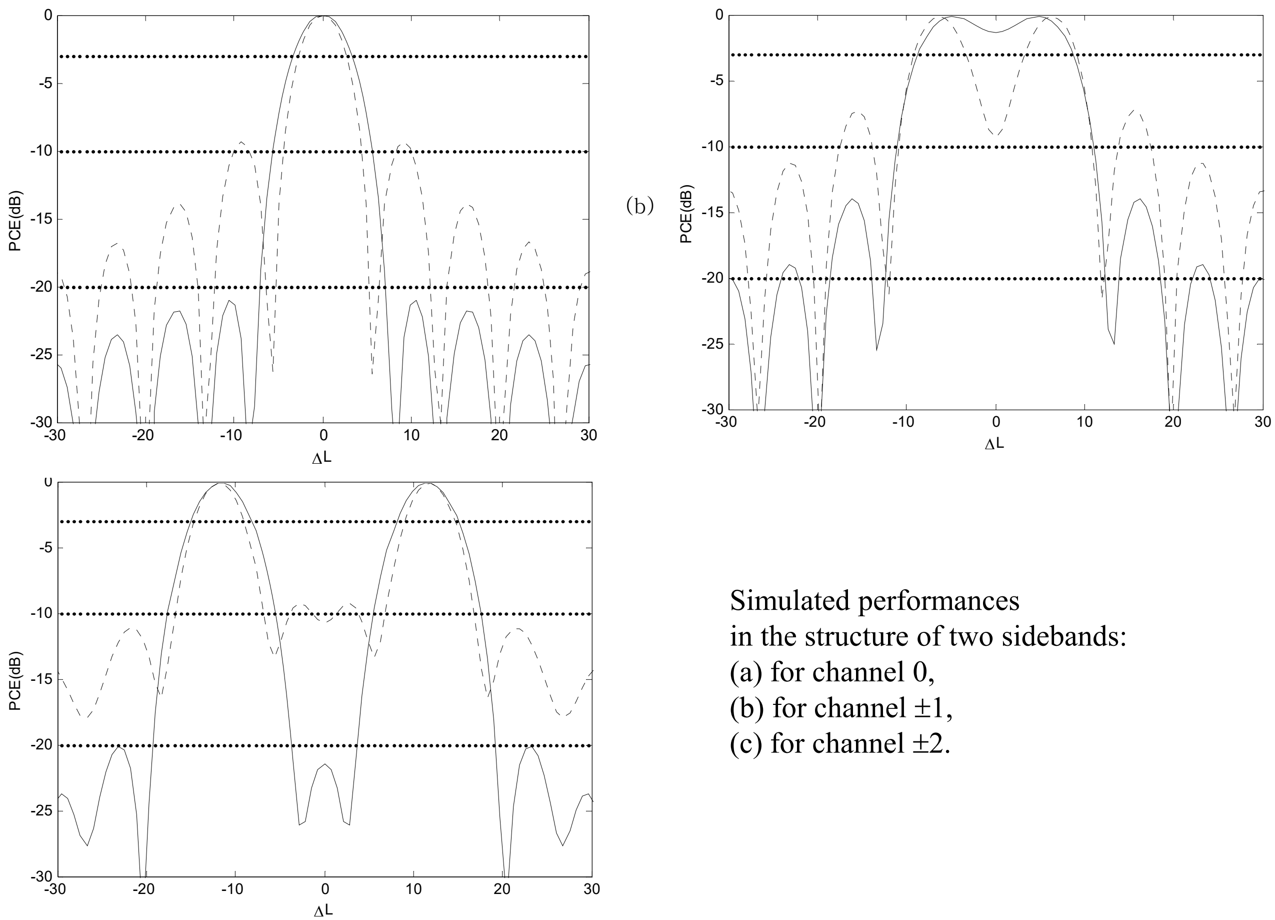
where C_{12} is the off-diagonal element of the matrix C

Simulation Result – Two Sidebands

(a)

(b)

(c)



Simulated performances
in the structure of two sidebands:
(a) for channel 0,
(b) for channel ±1,
(c) for channel ±2.

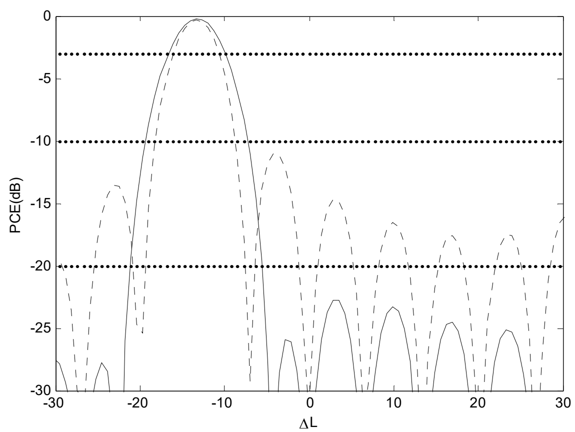
Matrix Formulation for Single Sideband

- The transfer matrix for single sideband configuration can be described except that the matrix $\mathbf{M}^{\boldsymbol{\Phi\beta}}$ is replaced with $\mathbf{M}^{\boldsymbol{\Phi}}$ if j is the even number and $\mathbf{M}^{\boldsymbol{\Phi\alpha}}$ otherwise.

- φ_α and φ_β are used instead of φ, respectively where

$$\varphi_\alpha = (\beta_1 - \beta_2) l_{p\alpha}$$
$$\varphi_\beta = (\beta_1 - \beta_2) l_{p\beta}$$

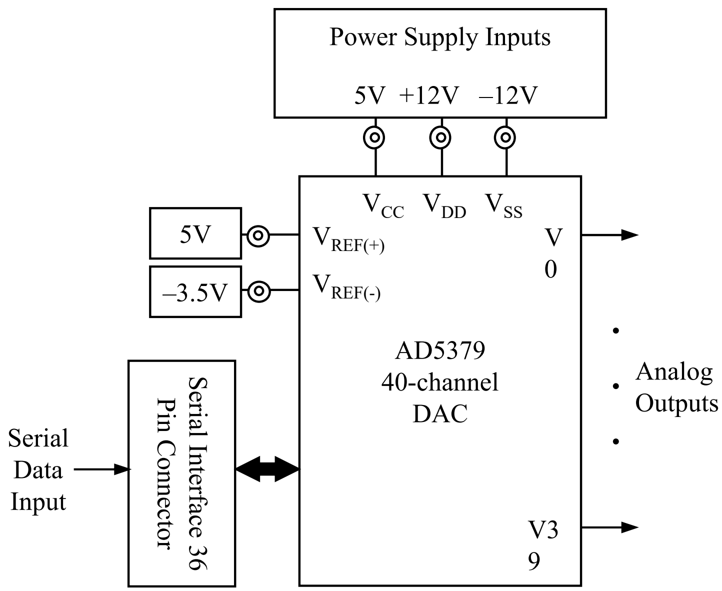
- Simulated performance in the single sideband configuration for channel –2



IV. Electronic Driving Circuit for EMF

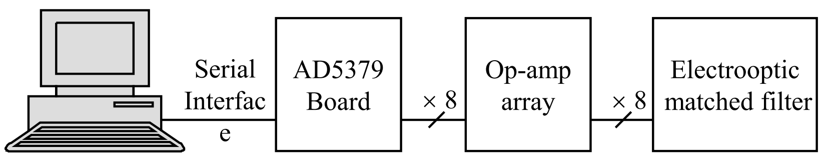
A. Digital-to-Analog Converter Driving Circuit

- The EMF is controlled by applying different voltages to each electrode set independently
- The AD5379 contains 40 DACs in one package and provides the maximum output voltages span of 17.5 V



Electronic Driving Circuit Configuration

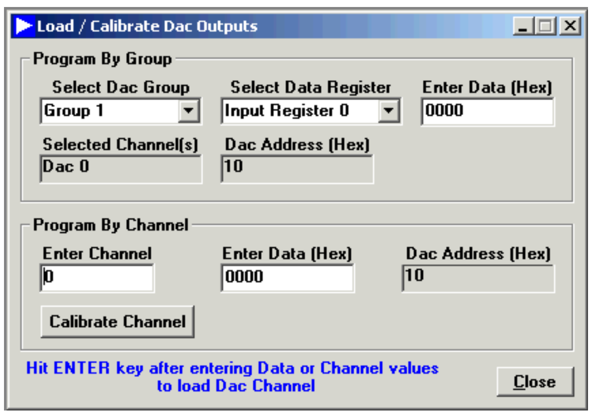
- In this research, programmable data inputs are loaded from a personal computer memory into the AD5379 input registers by serial interface
- The DAC output voltages are insufficient to directly drive the EMF, so an external op-amp array is utilized to obtain higher voltages



IV. Electronic Driving Circuit for EMF

B. Loading DAC Channels

- All channels or each channel can be loaded manually with the entered DAC code
- The AD5379 accepts 14-bit data word format for the serial interface



14-bit data word	Hexidecimal	Offset
11 1111 1111 1111	3FFF	+8191
11 1111 1111 1110	3FFE	+8190
10 0000 0000 0001	2001	+1
10 0000 0000 0000	2000	0
01 1111 1111 1111	1FFF	-1
00 0000 0000 0001	0001	-8191
00 0000 0000 0000	0000	-8192

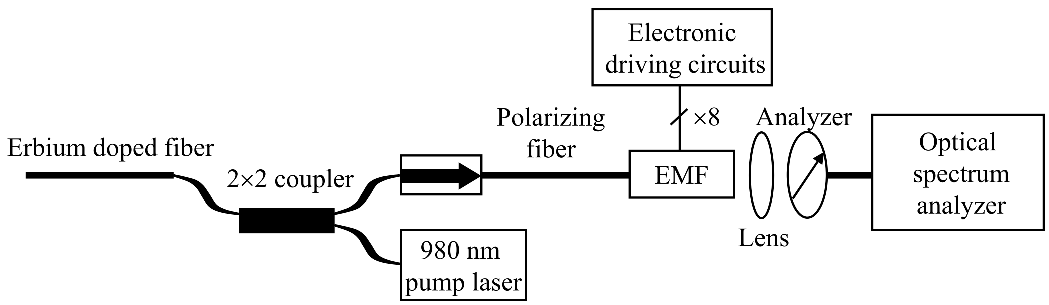
- The hexadecimal code can be decoded as follows:

$$V = \left(VOUT_{\max} \times \frac{HEX2DEC(Hex) - 8192}{8192} \right) \times G$$

V. Experimental Results

A. Experimental Configuration

- Optical testing was carried out using the amplified spontaneous emission (ASE) from a broadband light source of an erbium-doped fiber pumped by a 980 nm laser diode



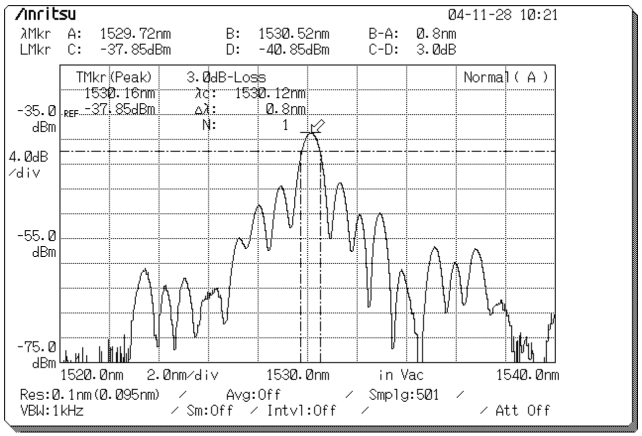
- External electronic circuits drive 8 independent sets of electrodes by using a DAC array
- The transmitted beam, after it passes through the EMF and the optical polarizer, is monitored with an optical spectrum analyzer

V. Experimental Results

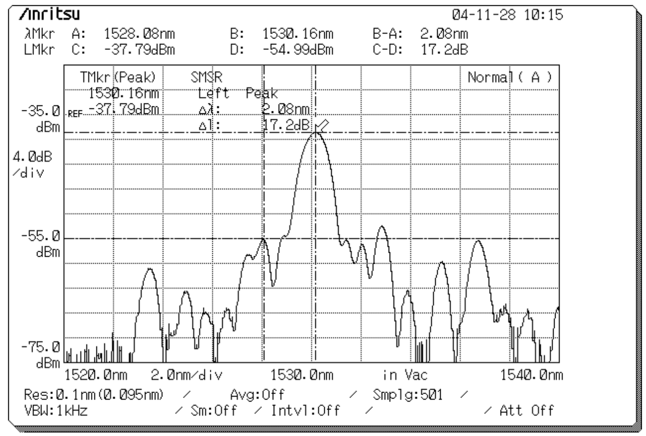
B. Test Results

› The optical output power spectra of EMF for TE→TM polarization conversion in the structure for two sidebands: (a) unapodized and (b) apodized filter responses of TM mode at channel 0

(a)



(b)

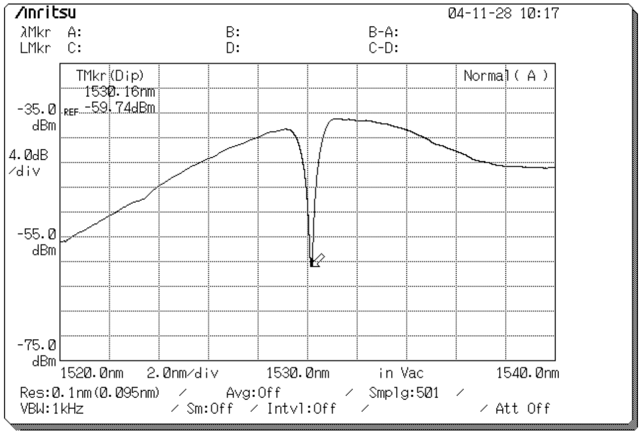


› A uniform coupling voltage $V_0 = 13$ V
› The optical bandwidth (FWHM) of 0.8 nm is in close agreement with the calculated value
› A sidelobe suppression level better than –17 dB is achieved

Test Result at Channel 0 Continued…

- The optical output power spectra of EMF for TE→TM polarization conversion in the structure for two sidebands: (c) apodized filter response of TE mode at channel 0

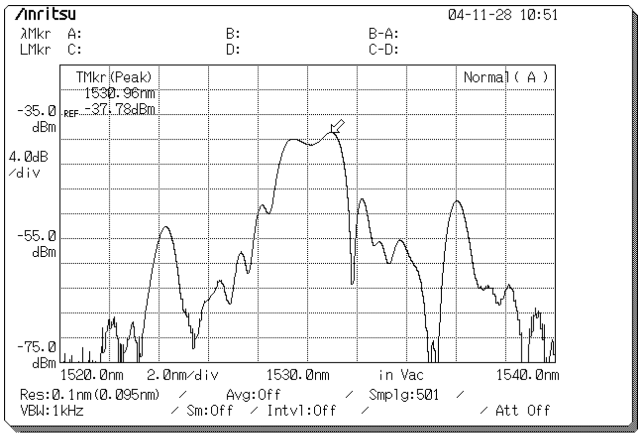
(c)



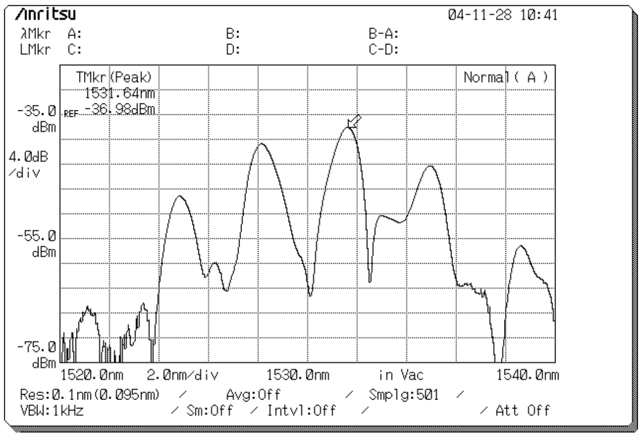
Test Results at Channel ±1 and ±2

- The optical output power spectra of EMF for TE→TM polarization conversion in the structure for two sidebands:
  (d) apodized output power responses of TM mode at channel ±1 and (e) channel ±2

(d)



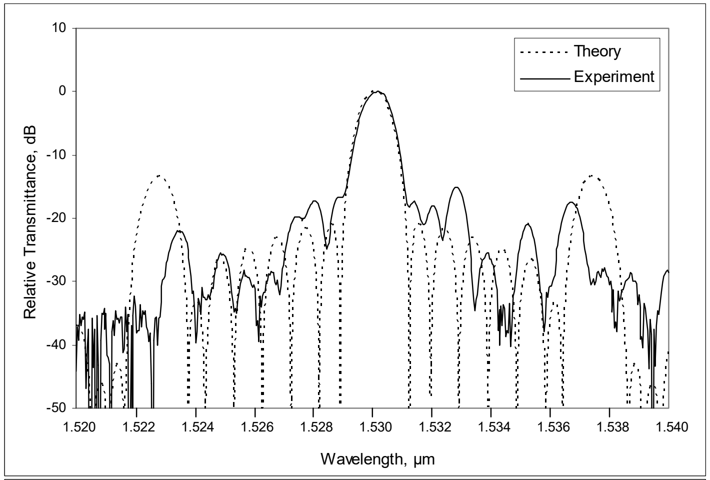
(e)



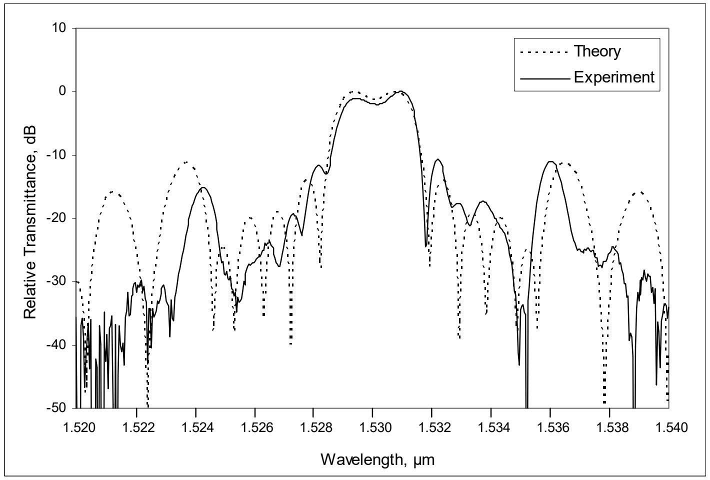
- The filter performance of TM→TE polarization conversion is similar to that of TE→TM conversion

Theoretical and Experimental Curves

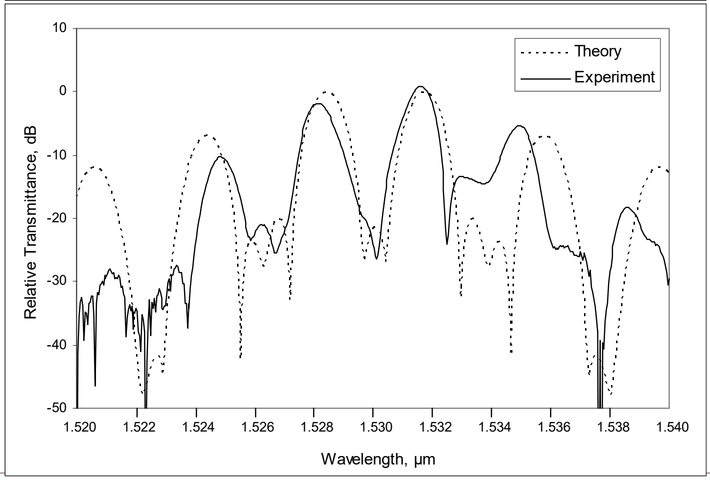
(a)



(b)



(c)



Theoretical and experimental curves for apodized EMF
filter characteristic :
(a) at channel 0,
(b) at channel ±1,
(c) at channel ±2.

VI. Conclusions

- The EMF is designed for operation in the 1530 nm spectral regime
- The device utilizes TE↔TM polarization conversion in a single mode waveguide fabricated in $LiNbO_3$ by Ti diffusion
- The performance of EMF - inherently independent of the input polarization because of the reciprocal characteristic between TE and TM mode polarization conversion
- The spectral tuning range of 3.2 nm for 5 channels is demonstrated. More channels can be accommodated by increasing the number of electrode sets (e.g., if P = 198, then N = 100) with the length of the device unchanged
- A tuning speed of less than 50 ns was achieved previously in a LiNbO3 tunable filter, and similar fast tuning is expected in the EMF
- Apodization improves the sidelobe suppression from –8.6 dB to –17.2 dB

VII. Recommendations

- The structure for single sideband with more than 8 electrode sets can realize good filter characteristics showing close agreement with prediction
- New electronic components to provide higher voltage supply can facilitate the experiments
- The EMF can be configured for a 4 port add-drop multiplexer and a two port bandpass filter of a Mach-Zehnder interferometer structure
- The spectral tuning range of the EMF for coarse WDM application can be improved by using a LiTaO3 substrate because the birefringence of $LiTaO_3$ is much less than that of $LiNbO_3$