Volume Grating Coupler-Based Optical Interconnect Technologies for Polylithic Gigascale Integration

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Volume Grating Coupler-Based Optical Interconnect Technologies for Polylithic Gigascale Integration

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Dedication

To my loving family

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List of Symbols

A_{chip}	Chip area
P_{chip}	Chip power dissipation
$P_{density}$	Power density
F_{clock}	Clock frequency
N_{tx}	Transistor count
$N_{I/O}$	ITRS-projected microprocessor I/O count
$C_{I/O}$	Cost per I/O
$d_{I/O}$	Via, I/O pad pitch
W_{trace}	Substrate electrical interconnect trace width
d_{trace}	Substrate electrical interconnect edge-to-edge trace spacing
$N_{I/O'}$	Revised total I/O count (ITRS projected I/O count + N_{GF2C})
N_{GF2C}	Number of I/O required for gigascale fiber-to-the-chip communication
N_{layers}	Number of substrate-level electrical interconnect trace layers (based on ITRS projections)
$N_{layers'}$	Revised number of substrate-level electrical interconnect trace layers (based ITRS projections + Gigascale fiber-to-the-chip considerations)
N_{ch}	Number of multiplexed electrical channels per optical I/O
$B_{Elec\text{-}Sub}$	Substrate-level electrical interconnect bit-rate
$N_{I/O,Elec\text{-}Opt}$	Number of signal I/O connecting microprocessor and optoelectronic die
r_{via}	Escape via radius
L_{trace}	Substrate electrical interconnect trace length
K_o	Electrical interconnect bandwidth constant

List of Symbols (Cont'd)

N_{trace}	Number of allowed escape traces between escape vias
TG	ITRS technology generation
V_{dd}	Supply voltage
L	CMOS transistor channel length
σ_{skew}	% local clock period consumed by skew
σ_{jitter}	% local clock period consumed by jitter
W_{opt}	Optimum on-chip interconnect width
W	On-chip interconnect width
τ	On-chip interconnect delay
c_o	Speed of light in a vacuum
ξ	Constant describing on-chip interconnect geometry
ρ	Metal resistivity
ε_o	Average relative permittivity
R_o	Output resistance of a minimum size repeater
C_o	Input capacitance of a minimum size repeater
$l_{elec\text{-}opt}$	Electrical-to-optical interconnect partition length
ε_r	Relative dielectric constant
N_{eff}	Effective refractive index of fundamental waveguide mode
D_{chip}	Chip edge length
$l_{elec\text{-}ext}$	Partition length between chip-level electrical interconnect and board-level electrical exterconnect
L_t	Total length of all interconnects longer than partition length

List of Symbols (Cont'd)

A_{opt}	Routing area of optical waveguide partition
d_{opt}	Optical waveguide pitch
A_{ext}	Routing area of electrical exterconnect partition
d_{ext}	Electrical exterconnect pitch
e_{part}	Routing efficiency of optical waveguide or electrical exterconnect partition
k	Rent's parameter
N_{gates}	Number of logic gates
p	Rent's exponent
λ_o	Free-space optical wavelength
F_{max}	Maximum on-chip global clock frequency
κ	Crosstalk coupling coefficient
d_{wg}	Edge-to-edge optical waveguide separation distance
K	Optical crosstalk constant
x	Propagation/longitudinal distance/direction
P_0	Initial power launched into source waveguide
P_{source}	Optical power in source waveguide
P_{victim}	Optical power in victim waveguide
L_{couple}	Crosstalk coupling distance
$n_{lower\text{-}clad}$	Lower-cladding refractive index
$n_{upper\text{-}clad}$	Upper-cladding refractive index
n_{core}	Core refractive index
ε	Relative permittivity

List of Symbols (Cont'd)

n_p	Prism refractive index
θ_V	Angle with respect to the normal of the lower prism-air interface
v	Mode reference index
k_o	Freespace wavevector
β_v	Propagation constant of v^{th} mode
n_{wg}	Waveguide film refractive index
$\theta_{zz,v}$	Zig-zag angle of the v^{th} guided-mode
$W_{half}(x)$	Beam half-width
W_{ap}	Aperture width
$W_{coupler}$	Volume grating coupler width
$L_{coupler}$	Volume grating coupler length
Λ	Grating period
λ_r	Holographic read wavelength
ϕ	Grating slant angle
$E_y(x,z)$	Electric field inside diffraction grating
ε_1	Amplitude of sinusoidal relative permittivity
K_x	x-component of grating vector
K_z	z-component of the grating vector
$\bar{K}$	Grating vector
$S_i(z)$	Amplitude of the i^{th} space-harmonic of the Fourier expansion of $E_y(x,z)$ along the direction of periodicity
$\bar{r}$	Unit vector

List of Symbols (Cont'd)

$\bar{\sigma}_i$	Floquet wavevector of i^{th} space harmonic
$\bar{\sigma}_{ix}$	x- component of Floquet wavevector of i^{th} space harmonic
$\bar{\sigma}_{iz}$	z- component of Floquet wavevector of i^{th} space harmonic
i	Space harmonic (diffracted order) reference index
$\bar{k}_2$	Wavevector of 0^{th} diffracted order in grating region
k_{2x}	x-component of 0^{th} order wavevector
k_{2z}	z-component of 0^{th} order wavevector
θ	Angle of refraction of incident plane wave within the grating region
θ_i	Angle of diffraction of space harmonic within grating region
θ_i'	Angle of diffraction of space harmonic into backward diffraction region
θ_i''	Angle of diffraction of space harmonic into forward diffraction region
θ'	Angle of incidence of plane wave incident on grating
m	Bragg condition index
A	Space harmonic coefficient matrix
S	Space harmonic matrix
$\dot{S}$	Space harmonic derivative matrix
a	Space harmonic coefficient matrix constant
b_i	Space harmonic coefficient matrix factor of i^{th} diffracted order
c_i	Space harmonic coefficient matrix factor of i^{th} diffracted order
l	Space harmonic amplitude reference index

List of Symbols (Cont'd)

C_m	Space harmonic constants determined from electromagnetic boundary conditions
$w_{l,im}$	Element of space harmonic component eigenvector found from coefficient matrix
λ_m	Eigenvalue of space harmonic component eigenvector found from coefficient matrix
N	Number of space harmonics retained for computation of coefficients
ε_I	Relative permittivity of forward diffraction region
ε_{III}	Relative permittivity of backward diffraction region
E_1	Normalized electric field of backward diffraction region
E_3	Normalized electric field of forward diffraction region
t_g	Grating region thickness
R_i	Normalized amplitudes of the i^{th} reflected wave in backward diffraction region
T_i	Normalized amplitudes of the i^{th} transmitted wave in forward diffraction region
$\bar{k}_{1i}$	Wavevector of i^{th} reflected wave in backward diffraction region
$\bar{k}_{3i}$	Wavevector of i^{th} transmitted wave in forward diffraction region
$\bar{k}_1$	Allowed wavevector in cover (backward diffraction) region
$\bar{k}_3$	Allowed wavevector in substrate (forward diffraction) region
H_x	Tangential component of magnetic field
μ	Relative permeability
ω	Angular frequency

List of Symbols (Cont'd)

δ_{i0}	Kronecker delta function
DE_{1i}	Diffraction efficiency of i^{th} diffracted order in backward diffraction region
DE_{3i}	Diffraction efficiency of i^{th} diffracted order in forward diffraction region
$N_{eff,v}$	Effective refractive index of v^{th} waveguide mode
$\theta_{i,v}$'	Angle of diffraction of v^{th} waveguide mode
α_v	Coupling coefficient of v^{th} mode
$\tilde{\gamma}_v$	Complex propagation constant of supported waveguide/grating mode
$\beta_{v,\mathrm{mod}}$	Propagation constant of v^{th} mode in presence of grating index modulation
$\eta_{p,i}$	Preferential coupling ratio of i^{th} diffracted order in region *p*
$P_{p,i}$	Power coupled into i^{th} diffracted order in region *p*
DE_{output}	Output diffraction efficiency
DE_{input}	Input diffraction efficiency
P_i	Time average power flow normal to the waveguide of i^{th} diffracted order
I_{out}	Out-coupled intensity profile at grating surface
I_{in}	Gaussian input intensity profile at grating surface
w_{beam}	Gaussian beam width
x_o	Relative longitudinal location of Gaussian peak
E_{1w}	Electric field of interferometric recording beam #1
E_{2w}	Electric field of interferometric recording beam #2

List of Symbols (Cont'd)

k_{x1w}	Wavevector of interferometric recording beam #1 in grating region
k_{x2w}	Wavevector of interferometric recording beam #2 in grating region
$n_{wg,w}$	Refractive index of grating material at write wavelength
λ_w	Holographic write wavelength
n_{pw}	Prism refractive index at write wavelength
I_w	Intensity profile of interference pattern of two recording beams
A_{1w}	Amplitude of interferometric recording beam #1
A_{2w}	Amplitude of interferometric recording beam #2
δ_{shrink}	Percent decrease in grating thickness (shrink) during thermal cure
K_{xs}	*x*-component of grating vector accounting for shrinkage
K_{zs}	*z*-component of grating vector accounting for shrinkage
θ_{a_1}	Angle of incidence of beam #1 at air-prism interface with respect to normal of grating layer
θ_{a_2}	Angle of incidence of beam #2 at air-prism interface with respect to normal of grating layer
θ_{1w}	Angle of incidence of beam #1 at air-prism interface with respect to normal of prism
θ_{2w}	Angle of incidence of beam #2 at air-prism interface with respect to normal of prism
θ_{g1}	Angle of refraction of k_{1w} in grating region with respect to normal of grating layer
θ_{g2}	Angle of refraction of k_{2w} in grating region with respect to normal of grating layer
θ_{p1}	Angle of incidence of beam #1 at prism-grating interface with respect to normal of grating layer

List of Symbols (Cont'd)

θ_{p2}	Angle of incidence of beam #2 at prism-grating interface with respect to normal of grating layer
$\Delta\theta$	Angular offset between two recording beams
α_{TE}	Grating coupling coefficient for fundamental mode under TE polarized light
α_{TM}	Grating coupling coefficient for fundamental mode under TM polarized light
A_n	Cauchy coefficient
B_n	Cauchy coefficient
C_n	Cauchy coefficient
P_{wg}	Power in optical waveguide
α_{wg}	Propagation loss coefficient
α_{rad}	Radiation loss coefficient
α_{abs}	Absorption loss coefficient
α_{scat}	Scattering loss coefficient
SSR	Sum of the square of residuals
q_h	h^{th} data point
$\hat{q}_h$	h^{th} fitted response value
`r_h	h^{th} residual difference between q_h and $\hat{q}_h$
h	Reference index
w_h	Residual weight
σ_h	Residual variance
`r_{adj}	Adjusted residuals

List of Symbols (Cont'd)

v_h	h^{th} leverage factor
u_{adj}	Standardized adjusted residuals
$`K$	Constant for standardized adjusted residuals
$`s$	Constant for standardized adjusted residuals
w_h	Robust bisquare weights
θ_{y-j}	Y-junction branching output half angle
L_{taper}	Length of taper region, Y-splitter
R_{couple}	Radius of curvature, 3 dB coupler
L_{couple}	Length of coupling region, 3 dB coupler
L_{MMI}	Length of MMI region
w_{MMI}	Width of MMI region
N_{output}	Fanout of MMI device
d_{MMI}	Pitch between MMI output waveguides
$\sigma_{TE,TM}$	Polarization factor, MMI device
$L_{MMI,acceptable}$	Acceptable range of MMI device lengths
$w_{MMI,acceptable}$	Acceptable range of MMI device widths
DR	Dynamic range of MMI output
max_{count}	Maximum pixel brightness count
min_{count}	Minimum pixel brightness count
ΔP_{MMI}	MMI output power uniformity
$max_{area,outputs}$	Maximum pixel count summation of MMI output
$min_{area,outputs}$	Minimum pixel count summation of MMI output

List of Symbols (Cont'd)

A_{det}	Detector area
$\Delta x_{\Delta\lambda}$	Maximum longitudinal optical beam width under wavelength variations
Δx	Maximum longitudinal placement variations due to solder attach process
Δy	Maximum transverse placement variations due to solder attach process
z_{f}	Nominal focal plane of focusing grating coupler
Δz	Maximum vertical placement variations due to solder attach process
$\Delta\lambda$	Range of wavelength variations
t_{solder}	Solder ball height
$t_{package}$	Chip-level package thickness
t_{wiring}	Multi-level wiring network thickness
Δt_{solder}	Vertical bump deviations
$\Delta x_{\Delta\lambda}$	Longitudinal beam width of focusing grating coupler under placement, wavelength variations
R_{bend}	Bend radius of waveguide bend
$P_{loss,bend}$	Power loss for waveguide bend
t_{wg}	Waveguide thickness

List of Abbreviations

CMOS	Complementary Metal Oxide Semiconductor
SIMOX	Separation by Implantation of Oxygen
VCSEL	Vertical Cavity Surface Emitting Laser
AR	Anti-Reflection
BEOL	Back-End-Of-Line
OMCVD	Organo-Metallic Chemical Vapor Deposition
LED	Light Emitting Diode
I-MSM	Inverted Metal-Semiconductor-Metal
MCM-L	Multi-Chip Module Laminated
TAB	Tape Automated Bonded
OETC	Optoelectronics Technology Consortium
OSA	Optical Subassembly
FAB	Fiber Array Block
POLO	Parallel Optical Link Organization
QFP	Quad Flat-Pack
BGA	Ball Grid Array
PONI	Parallel Optics for Network Interconnects
POSA	Parallel Optical Sub-Assembly
OL	Open-Loop
CL	Closed-Loop
CLAC	Closed-Loop with Active Compensation
PLL	Phase-Locked Loop

List of Abbreviations (Cont'd)

VCO	Voltage-Controlled Oscillator
ITRS	International Technology Roadmap for Semiconductors
DOE	Diffractive Optical Element
TIR	Total Internal Reflection
RLC	Resistive-Inductive-Capacitive
RC	Resistive-Capacitive
ToF	Time-of-Flight
ADI	Alternating Direction Implicit
PNB	Polynorbornene
MSQ	Methylsilsesquioxane
TMSNB	Tri-Methyl Substituted Norbornene
BPM	Beam Propagation Method
PECVD	Plasma Enhanced Chemical Vapor Deposition
ESD	Electrostatic Discharge
TE	Transverse Electric
TM	Transverse Magnetic
RCWA	Rigorous Coupled Wave Analysis
TNU	Thickness Non-Uniformity Parameter
STS	Surface Technology Systems
VASE	Variable Angle Spectroscopic Ellipsometry
UV	Ultra-Violet
RBLLS	Robust Bisquare Linear Least Squares

List of Abbreviations (Cont'd)

MAD	Median Absolute Deviation
FWHM	Full Width at Half Max
DR	Dynamic Range
MMI	Multi-Mode Interference
FDTD	Finite Difference Time Domain
MSE	Mean Square Error

Summary

The concept of polylithic integration of electrical and optical interconnect technologies is presented. The use of a two-grating, or grating-to-grating, coupling path for board-to-chip coupling of optical signals is proposed for fiber-to-the-chip and intra-chip optical clock distribution applications. An estimate for the increase in electrical I/O and substrate-level electrical interconnect layers required for a 40 Tb/s fiber-to-the-chip communication system using grating-to-grating board-to-chip coupling of optical signals is provided. An estimate of the ITRS technology generation within which alternate methods of intra-chip clock distribution are required is identified, and the strengths and weaknesses associated with different methods of optical clock distribution are summarized. A partition length between and routing area associated with on-chip optical waveguides and board-level electrical exterconnects is provided for signal distribution in gigascale microprocessors.

In addition, Avatrel 2190P is investigated as a candidate material for the creation of integrated optical waveguides and power splitters. Low-decomposition-temperature sacrificial polymers are used to construct chip-length embedded air-clad optical waveguides for on-chip signal and clock distribution. A wafer-level batch package exhibiting compatible electrical and optical I/O interconnects is presented, where two-material index-defined and air-clad waveguide/grating channels are fabricated and tested. Finally, grating-to-grating coupling over a quasi-free space coupling path is demonstrated and quantified for the first time to illustrate the feasibility of board-to-chip optical I/O in gigascale microprocessor systems.