Electrically Pumped SPASER

Dmitry Yu. Fedyanin and Aleksey V. Arsenin

Laboratory of Nanooptics and Femtosecond Electronics, Department of General Physics, Moscow Institute of Physics and Technology (State University)
OUTLINE

- Data-Processing Devices
- SPPs and SPP losses
- SPP Amplification
- SPASER
- Active Plasmonic Interconnects
- Summary
Data-Processing Devices

Nvidia GeForce GTX 680

Number of CUDA cores: 1536
Performance: 3.09 TFLOPS

The problem is that after each 1-5 float point operations, one has to write or read information or transmit data to another core.

Ideally, the required bandwidth for the memory interface should be equal to 3090 GB/s keeping a ratio of 1 byte/FLOP.

Actual bandwidth is only 192.2 GB/s, but memory interface width is 256-bit. So, we have only 0.75 GB/s per line.
**Data-Processing Devices: Copper Interconnects**

**Twin-Wire Line Model**

**Electrical interconnect limitations:**

1) Propagation losses.
2) $\tau = RC$ results in a delay and a rise time.
3) Miniaturizing the system doesn't reduce $RC$ delay.

\[ B < B_0 \frac{d^2}{l^2}, \text{where } B_0 < 10^{16} \text{ bit/s} \]

If $d < \frac{l}{1000}$, then $B < 1\text{ GB/s}$


Twin-Wire Line Model

Electrical interconnect limitations:
1) Propagation losses.
2) $\tau = RC$ results in a delay and a rise time.
3) Miniaturizing the system doesn’t reduce $RC$ delay.

We have almost achieved the bandwidth limit of a single copper line (wire).

We can further increase the total bandwidth only by increasing the number of lines (wires).

But it is not possible, since today we have more than 256 lines in chip-to-chip interconnects and much higher number in on-chip interconnects.

$B < B_0 \frac{d^2}{l^2}$, where $B_0 < 10^{16}$ bit/s

if $d < 1000$, then $B < 1$ GB/s

Data-Processing Devices: **Optical Interconnects**

Higher bandwidth, lower delays, lower power consumption, similar interconnect dimensions, lower cross-talk

Utilizing on-chip optical interconnects, it becomes possible to achieve exaflop computing on a single chip.

Figure: http://domino.research.ibm.com/
CMOS integrated silicon nanophotonics gives silicon nanophotonics devices a possibility to share the same silicon layer with silicon transistors and design On-Chip and Chip-to-Chip interconnects.

Is it possible to suggest another approach, which is more compact, have the same bandwidth and the same delays?
SPPs

Drude model:
\[ \varepsilon_1(\omega) = \varepsilon_r - \frac{\omega_p^2}{\omega^2 + i\Gamma \omega} \]
\[ \varepsilon_1 = \Re(\varepsilon_1) + i \Im(\varepsilon_1) \]
\[ \Re(\varepsilon_1) < 0 \]
\[ k_x = \Re(k_x) + i \Im(k_x) \]

\[ \lambda_{\text{SPP}} = \frac{2\pi}{\Re(k_x)} \] - SPP wavelength

\[ L_{\text{SPP}} = \frac{1}{2 \Im(k_x)} \] - propagation length

\[ \rho_i = \frac{1}{\Re(\kappa_i)} \] - penetration depths

SPP dispersion
\[ \kappa_1 \varepsilon_2 = -\kappa_2 \varepsilon_1 \]
SPP losses

1550 nm
SPP losses

\[ \lambda = 1.55 \, \mu m \]
\[ \lambda_{SPP} \approx 1.5 \, \mu m \]
\[ L_{SPP} \approx 270 \, \mu m \]
\[ \rho_{\text{Air}} \approx 2.5 \, \mu m \]
\[ \rho_{\text{Au}} \approx 0.023 \, \mu m \]
SPP losses

\( \lambda = 1.55 \ \mu m \)

\( \lambda_{SPP} \approx 1.5 \ \mu m \)

\( L_{SPP} \approx 270 \ \mu m \)

\( \rho_{\text{Air}} \approx 2.5 \ \mu m \)

\( \rho_{\text{Au}} \approx 0.023 \ \mu m \)
### SPP losses

<table>
<thead>
<tr>
<th>Material</th>
<th>Density ($\rho$)</th>
<th>$\lambda_{\text{SPP}}$</th>
<th>$L_{\text{SPP}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Air</td>
<td>$\approx 2.5 \ \mu m$</td>
<td>$= 1.55 \ \mu m$</td>
<td>$\approx 270 \ \mu m$</td>
</tr>
<tr>
<td>Au</td>
<td>$\approx 0.023 \ \mu m$</td>
<td>$= 1.55 \ \mu m$</td>
<td>$\approx 270 \ \mu m$</td>
</tr>
<tr>
<td>Si</td>
<td>$\approx 0.2 \ \mu m$</td>
<td>$= 1.55 \ \mu m$</td>
<td>$\approx 5.8 \ \mu m$</td>
</tr>
<tr>
<td>Au</td>
<td>$\approx 0.022 \ \mu m$</td>
<td>$= 0.42 \ \mu m$</td>
<td>$\approx 5.8 \ \mu m$</td>
</tr>
</tbody>
</table>
SPP losses

\[
\text{Im} \beta \approx \frac{\omega}{2c} \frac{\varepsilon_2^{3/2}}{\left(1 + \frac{\varepsilon_2}{\text{Re} \varepsilon_1}\right)^{3/2}} \frac{\text{Im} \varepsilon_1}{\left(\text{Re} \varepsilon_1\right)^2} \Rightarrow L_{\text{SPP}} \propto \left(1 + \frac{\varepsilon_2}{\text{Re} \varepsilon_1}\right)^{3/2} \frac{\varepsilon_2^{3/2}}{\varepsilon_2^{3/2}}
\]
**SPP losses**

Low-loss
Not-confined

\[ \lambda = 1.55 \ \mu m \]
\[ \lambda_{SPP} \approx 1.5 \ \mu m \]
\[ L_{SPP} \approx 270 \ \mu m \]
\[ \rho_{\text{Air}} \approx 2.5 \ \mu m \]
\[ \rho_{\text{Au}} \approx 0.023 \ \mu m \]

Very lossy
Highly confined

\[ \lambda = 1.55 \ \mu m \]
\[ \lambda_{SPP} \approx 0.42 \ \mu m \]
\[ L_{SPP} \approx 5.8 \ \mu m \]
\[ \rho_{\text{Si}} \approx 0.2 \ \mu m \]
\[ \rho_{\text{Au}} \approx 0.022 \ \mu m \]
SPP Amplification

High propagation losses due to Joule heating restrict the application of SPPs. **Thus, one only way to overcome propagation losses is to partially or fully compensate Joule heating losses in the metal.** This can be done by using an active gain medium placed near a metal surface and pumping it.

- and many other papers
SPP Amplification: Optical Pumping


**Pumping:** frequency-doubled, mode-locked Ti:Sa laser (λ=405 nm, pulse length 100 fs).

**Threshold:** of the order of 1 GW/cm$^2$ at room temperature and about 60 MW/cm$^2$ at 10 K.


**Pumping:** pulsed laser (λ=1.06 μm, pulse length 140 ns)

**Threshold:** about 60 kW/cm$^2$ at room temperature
**SPP Amplification: Optical Pumping**


  **Pumping:** frequency-doubled, mode-locked Ti:Sa laser (λ=405 nm, pulse length 100 fs).

  **Threshold:** of the order of $1 \text{ GW/cm}^2$ at room temperature and about $60 \text{ MW/cm}^2$ at 10 K.


  **Pumping:** pulsed laser (λ=1.06 μm, pulse length 140 ns)

  **Threshold:** about 60 kW/cm$^2$ at room temperature

**Optical pumping requires the use of external high-power bulky pump lasers and is not feasible in ultracompact on-chip optical circuits**
Is it possible to design a COMPACT plasmonic structure with NEGLIGIBLY SMALL PROPAGATION LOSSES?

Requirements:
- Compact pumping
- Full loss compensation
- Compatibility with compact plasmonic and optical waveguides
SPP Amplification

Is it possible to design a COMPACT plasmonic structure with NEGLIGIBLY SMALL PROPAGATION LOSSES?

Requirements:
- Compact pumping
- Full loss compensation
- Compatibility with compact plasmonic and optical waveguides

The answer is electric pumping!

SPP Amplification

Au \quad x \quad \text{semiconductor}

\text{penetration depth}

L
SPP Amplification: Electric Pumping

Usually, Schottky diodes are treated as majority carrier devices. However, the situation changes drastically when the barrier height exceeds the half of the bandgap. In this case an inversion layer is formed near the metal-semiconductor contact. Under sufficient forward bias this carriers are injected into the bulk of the semiconductor and recombine with majority carriers.

Condition for net stimulated emission or gain

\[ F_e - F_h \geq \hbar \omega \geq E_g \]

SPP Amplification: Electric Pumping

Usually, Schottky diodes are treated as majority carrier devices. However, the situation changes drastically when the barrier height exceeds the half of the bandgap. In this case an inversion layer is formed near the metal-semiconductor contact. Under sufficient forward bias these carriers are injected into the bulk of the semiconductor and recombine with majority carriers.

To satisfy the condition for net stimulated emission or gain, the barrier height must be greater than or approximately equal to the bandgap of the semiconductor.

It's not usually possible, however ...

Fermi level in the metal occurs 130 meV above the conduction band edge of InAs ($E_g=0.40$ eV at 77K). Consequently, the barrier height of an Au/p-InAs contact is greater than the bandgap.

We solve six nonlinear first order differential equations that describe the carrier behavior within the semiconductor:

\[
\begin{align*}
\frac{d\varphi}{dz} &= -E_z \\
\frac{dE_z}{dz} &= 4\pi e (p - n + N_d) / \varepsilon_st \\
\frac{dn}{dz} &= \frac{1}{eD_n} J_n - \frac{\mu_n n}{D_n} E_z \\
\frac{dp}{dz} &= -\frac{1}{eD_p} J_p + \frac{\mu_p p}{D_p} E_z \\
\frac{dJ_n}{dz} &= eU \\
\frac{dJ_p}{dz} &= -eU
\end{align*}
\]

where \( U = U_{stim} + U_{spont} + U_{Auger} \)
SPP Amplification: Electrical Pumping

Together with six boundary conditions

\[
\begin{align*}
J_n |_{z=0} &= e\nu_{nr} (n |_{z=0} - n_0) \\
J_p |_{z=0} &= -e\nu_{pr} (p |_{z=0} - p_0) \\
\phi |_{z=0} &= -\psi_M - \chi_e \\
\phi |_{z=L} &= V + \frac{k_B T}{e} \ln\left(\frac{n_L}{N_c}\right) \\
n |_{z=L} &= n_i \\
p |_{z=L} &= p_i
\end{align*}
\]

Where

\[
\nu_{nr} \approx \frac{1}{4} \sqrt{\frac{8k_B T}{\pi m_n}}; \quad \nu_{pr} \approx \frac{1}{4} \sqrt{\frac{8k_B T}{\pi m_p}}
\]
SPP Amplification: Electrical Pumping

Stimulated emission and gain

\[ U = U_{\text{spont}} + U_{\text{Auger}} + U_{\text{stim}} \]

\[ U_{\text{stim}}(z) = g \left( F_e(z), F_h(z) \right) S / \hbar \omega \]

\[ g = \frac{4 \pi^2 e^2}{c \bar{n} m_c \bar{m}_0 \omega} \left| M_b \right|^2 \int_{0}^{+\infty} \left| M_{\text{env}}(E, E - \hbar \omega) \right|^2 \]

\[ \rho_c(E - E_c) \rho_v(E_v - E + \hbar \omega) \times \]

\[ \left\{ \frac{1}{1 + \exp\left(\frac{E - F_e}{k_B T}\right)} \right\} \frac{1}{1 + \exp\left(\frac{E - \hbar \omega - F_h}{k_B T}\right)} dE \]

- Gaussian Halperin-Lax band-tail (GHLBT) model
- Stern's envelope matrix element \( M_{\text{env}} \)

\[ N_a = 2.33 \times 10^{18} \text{ cm}^{-3} \]
\[ \hbar \omega = 0.3925 \text{ eV} \ (\lambda = 3.16 \mu\text{m}) \]
\[ \bar{n} = 3.50 \]
\[ L = 2.0 \mu\text{m} \]
\[ T = 77 \text{ K} \]
SPP Amplification: Electric Pumping

Stimulated emission and gain

\[ U = U_{\text{spont}} + U_{\text{Auger}} + U_{\text{stim}} \]

\[ U_{\text{stim}} (z) = g \left| F_{e}(z), F_{h}(z) \right| S(z) / \hbar \omega \]

\[ g = \frac{4 \pi^2 e^2}{c \, \hbar \, m_e^2 \omega} \left| M_b \right|^2 \int_0^{+\infty} \left| M_{\text{env}} (E,E - \hbar \omega) \right|^2 \]

\[ \rho_c (E - E_c) \rho_v (E_v - E + \hbar \omega) \times \]

\[ \left\{ \frac{1}{1 + \exp \left[ (E - F_e) / k_B T \right]} \right\} \]

\[ \frac{1}{1 + \exp \left[ (E - \hbar \omega - F_h) / k_B T \right]} \]

\[ \approx 1.41 \times 10^{-14} \left[ \min(n, p) - 5 \times 10^{14} \right] \]


\[ N_a = 2.33 \times 10^{18} \text{ cm}^{-3} \]

\[ \hbar \omega = 392.5 \text{ meV} \ (\lambda = 3.16 \mu\text{m}) \]

\[ \tilde{n} = 3.50 \]

\[ L = 2.0 \mu\text{m} \]

\[ T = 77 \text{ K} \]
SPP Amplification: Electric Pumping

SPP Amplification: Electric Pumping

Coherent SPP Sources

**SP^2ASER** and **SPASER**

Propagating plasmons and Localized plasmons
SP\textsubscript{P}ASER and SPASER

Short-range SPP

Threshold condition in a steady state:

\[ G_{\text{th}} = \frac{1}{2l} \ln \left( \frac{1}{|r|^2 |R|^2} \right) \]

Smooth facets:

\[ |r|^2 = |R|^2 \approx \left| \frac{\beta c}{\omega} - 1 \right|^2 \]

= 0.31 => \[ G_{\text{th}} = 115 \text{ cm}^{-1}, J_{\text{th}} = 4.4 \times 10^4 \text{ A/cm}^2 \] at \( l = 100 \mu\text{m} \)
Threshold condition in a steady state:

\[ G_{\text{th}} = \frac{1}{2l} \ln \left( \frac{1}{|r|^2 |R|^2} \right) \]

Smooth facets:

\[ |r|^2 = |R|^2 \approx \left| \frac{\beta c}{\omega} - 1 \right|^2 \approx 0.31 \Rightarrow G_{\text{th}} = 115 \text{ cm}^{-1}, \quad J_{\text{th}} = 4.4 \times 10^4 \text{ A/cm}^2 \text{ at } l = 100 \mu\text{m} \]
Threshold condition in a steady state:

\[ G_{th} = \frac{1}{2l} \ln \left( \frac{1}{|r|^2|R|^2} \right) \]

15-nm Au coating:

\[ |r|^2 = |R|^2 \approx \left| \frac{\beta c}{\omega} - 1 \right|^2 \approx 0.9 \implies G_{th} = 95 \text{ cm}^{-1}, \quad J_{th} = 4.0 \times 10^4 \text{ A/cm}^2 \text{ at } l = 10.2 \text{ µm} \]
This structure is a spaser-based laser, since it emits light. To design a true SPASER, an SPP inside the cavity should be coupled to an SPP outside the cavity.

Threshold condition in a steady state:

\[
G_{\text{th}} = \frac{1}{2l} \ln \left( \frac{1}{|r|^2 |R|^2} \right)
\]

15-nm-thick Au mirrors:

\[
|r|^2 = |R|^2 \approx \left[ \frac{\beta c}{\omega} - 1 \right] \frac{\beta c}{\omega + 1}
\]

\[= 0.9 \Rightarrow G_{\text{th}} = 95 \text{ cm}^{-1}, J_{\text{th}} = 4.0 \times 10^4 \text{ A/cm}^2 \text{ at } l = 10.2 \mu\text{m} \]
$l = 10.2 \mu m$

$d = 20 \text{ nm}$

$D = 100 \text{ nm}$

$L = 2 \mu m$

$h \sim 2 \mu m$

$|R|^2 = 0.98$

$|r|^2 = 0.89$

$|t|^2 = 0.07$

$J_{th} = 3.3 \times 10^4 \text{ A/cm}^2$

Active Plasmonic Interconnects

What about shrinking the lateral (y) dimension?
Active Plasmonic Interconnects

What about of shrinking the lateral (y) dimension?

All integrated circuits (both optical and electrical) are actually planar, 2D dimensional circuits. It means that the mode height is not as important as the mode width, which actually determines the crosstalk and integration density. So, we should decrease the waveguide width. In the present approach, there are no fundamental and technological limitations for shrinking the lateral (y) dimension of the considered structure down to several hundred nanometers, since there are only 2 characteristic dimensions: thickness of the inversion layer and thickness of the depletion region. Both of them are appreciably less than 100 nm.
Active Plasmonic Interconnects

Photonic TE\textsubscript{00} and TM\textsubscript{10} modes are very leaky modes and their propagation lengths are much shorter than propagation length of the plasmonic TM\textsubscript{00} mode.

Active Plasmonic Interconnects

\[ \varepsilon_m = -535 + 35i \quad \text{(Au)} \]
\[ \varepsilon_d = 2.16 \quad \text{(SiO}_2\text{)} \]
\[ \varepsilon_s = 12.25 \quad \text{(InAs)} \]
\[ \lambda = 3.16 \mu m \]
\( \tilde{n}(x,y) \) is real part of the refractive index of the medium at \((x,y)\)

\( u_g \) is the SPP group velocity

\( \xi(x,y) \) is approximately equal to \( \tilde{n}^2(x,y) \) in the semiconductor and and in the insulator and equals \( 1+\omega_p^2/(\omega^2+\Gamma^2) \) in the metal.

\[
F_p(x,y) = 1 + \frac{c^3 |E(x,y)|^2}{4\tilde{n}(x,y)\omega^2 u_g \int\int_{-\infty}^{+\infty} \frac{1}{16\pi} \left( \xi(\tilde{x},\tilde{y})|E(\tilde{x},\tilde{y})|^2 + |H(\tilde{x},\tilde{y})|^2 \right) d\tilde{x} d\tilde{y}},
\]

\[
F_p(x,y) < 3.5
\]
Summary

- Despite the advantages of silicon photonics, even smaller interconnects are achievable with SPP based waveguides, which have the similar bandwidth and delays.
- SPP waveguides are quite lossy. However, one can partially or fully compensate losses using an active medium placed near the metal surface.
- Optical pumping is very bulky and cannot be used in nanoscale on-chip circuits and we should move to electric pumping.
- I've demonstrated an amplification scheme, which is based on a Schottky barrier diode that give a possibility to obtain net SPP gain.
- The presented approach give a possibility do design an electrically pumped SPASER.
- The obtained threshold current is relatively small for a pulsed and even a cw SPASER.
- There are no physical limitations for shrinking the lateral dimension of the proposed structure down to deep-subwavelength scale and development of on-chip plasmonic interconnects.
Thank you for your attention!

E-MAIL: FEDDU@MAIL.RU
WEB: HTTP://NANO.PHYSTECH.EDU