Accurate Laser Model for Electrically Injected Monolithic GaAs on Silicon Nano-ridge Laser Diodes

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Abstract: We present a semi-analytical model that explains the working principle behind electrically injected $In_{0.2}Ga_{0.8}As$/GaAs-on-silicon monolithic nano-ridge laser diodes. We show how the model can be used to study the spectral behavior and the threshold gain.

1. Introduction

In the field of silicon photonics, monolithic integration of III-V materials on silicon is considered the ultimate integration approach in terms of scalability and reduced cost but it is quite challenging due to the large mismatch in crystal lattice constants and polarity that lead to formation of defects severely limiting the carrier lifetime, thereby hampering efficient light emission [1]. By employing selective area growth over confined regions to restrict defects in narrow oxide trenches and growing the III-V material out of the trench for high modal gain by nano-ridge engineering [2], optically pumped $In_{0.2}Ga_{0.8}As$/GaAs multi-quantum well nano-ridge lasers emitting around 1020nm were reported [3]. Given the small dimensions of these devices, electrical pumping remains challenging but was successfully demonstrated exploiting a mode beating effect to reduce losses [4]. Here, we develop a semi-analytical model which explains these results and will allow further optimization of these devices in the future.

2. Results and Discussion

We consider a nano-ridge waveguide with a periodic array of tungsten plugs (with contact pitch of 4.8µm) for current injection integrated on top as shown in Figure 1(a) with a cross-section as shown in Figure 1(b) . Using the Lumerical FDTD solver [5], we calculated the loss for the TE00 mode travelling through this structure by putting a modal source at z=0 and two power monitors at z=50µm and z=100µm and considering an exponential power decay. The simulated transmission spectrum shown in Figure 1 (c) exhibits dips in the loss. Inspecting the field pattern at 1.035µm, the wavelength with the lowest loss, we notice a beating pattern with a beating length of 1.6µm as shown in Figure 1(d). Further inspection reveals that this pattern originates from mode beating between the TE00 and TEM02 modes and results in a reduced overlap with the lossy metal.

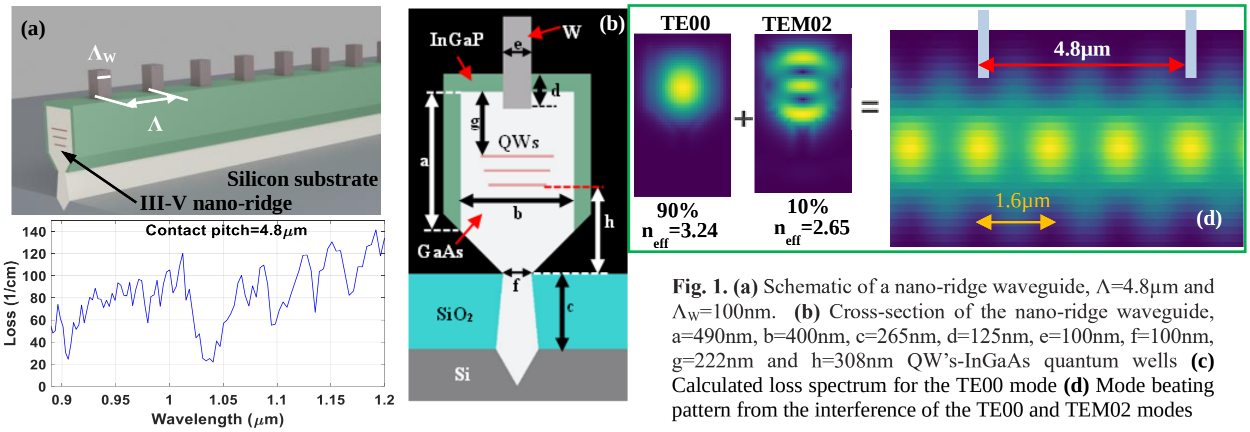

Fig. 1. (a) Schematic of a nano-ridge waveguide, Λ=4.8µm and Λ_W=100nm. **(b)** Cross-section of the nano-ridge waveguide, a=490nm, b=400nm, c=265nm, d=125nm, e=100nm, f=100nm, g=222nm and h=308nm QW's-InGaAs quantum wells **(c)** Calculated loss spectrum for the TE00 mode **(d)** Mode beating pattern from the interference of the TE00 and TEM02 modes

To gain more insight, we developed an analytical model for the device by solving the coupled differential equations for the electric field of the modes. The powers in the TE00 and TEM02 modes are:

$$P_1(z) = \left(\cos(sz) - j\frac{\delta}{s}\sin(sz)\right)\left(\cos(sz) - j\frac{\delta}{s}\sin(sz)\right)^* e^{-2Im(\tilde{\beta})z} \quad \text{For the TE00 mode} \qquad (1)$$

$$P_2(z) = \left(\frac{\kappa_{21}}{s}\sin(sz)\right)\left(\frac{\kappa_{21}}{s}\sin(sz)\right)^* e^{-2Im(\tilde{\beta})z} \quad \text{For the TEM02 mode} \qquad (2)$$

where parameters are as defined in Table 1.

Exporting electric field data, effective refractive indices for the two modes and permittivity data from FDE Mode and calculating overlap integrals by performing numerical integration in Matlab, we evaluated the coupling coefficients and calculated the power spectrum of the two modes at different positions from the source and compared these results with FDTD simulation results as shown in Figure 2 (a) and (b). We can observe from these graphs that around the 1.035µm wavelength, where the coupling between TE00 and TEM02 mode coupling occurs, the results from the analytical expressions and the simulations are in agreement.

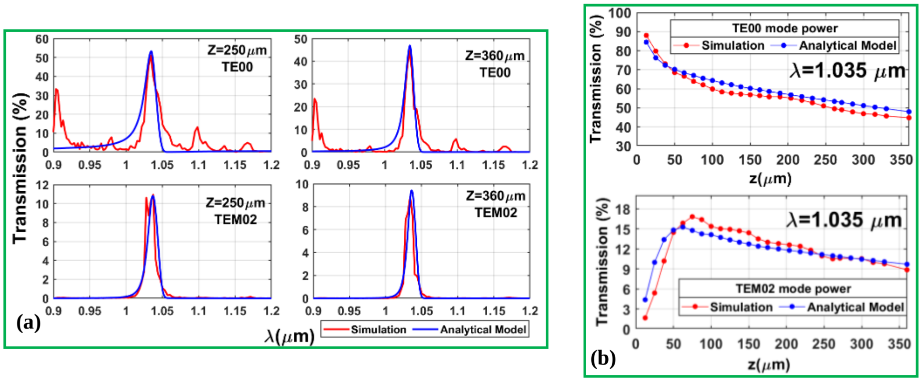

Fig. 2. Comparison between analytical results and simulation results of: **(a)** TE00 and TEM02 mode power spectra at different positions along the length of nano-ridge waveguide. **(b)** TE00 and TEM02 mode power at zero detuning wavelength at different z positions from the source.

Based on the solutions of the coupled mode equations and numerically calculated reflection coefficients, we were able to derive a round-trip matrix. Propagation constants now also include gain and extra losses due to scattering, leakage to substrate and free-carrier absorption in doped regions. Lasing then is obtained for an eigenvalue of 1 of this round-trip matrix. We calculated the threshold gain to be 792/cm for a device length of 1502.4µm by a self-written Matlab code. Figures 3 (a) and (b) show the calculated eigenvalue magnitude and phase. Points in red color are wavelength points with zero phase and the point at 1035.65nm satisfies the laser condition as shown in Figure 3 (b) and (c). Meanwhile, the eigenvector corresponding to this matrix with an eigenvalue of 1 gives a certain combination of TE00 and TEM02 modes that leads to lasing in the cavity. We can see from Figure 3 (d) that 89% of TE00 and 11% of TEM02 is the combination of modes that case lase around 1.035µm.

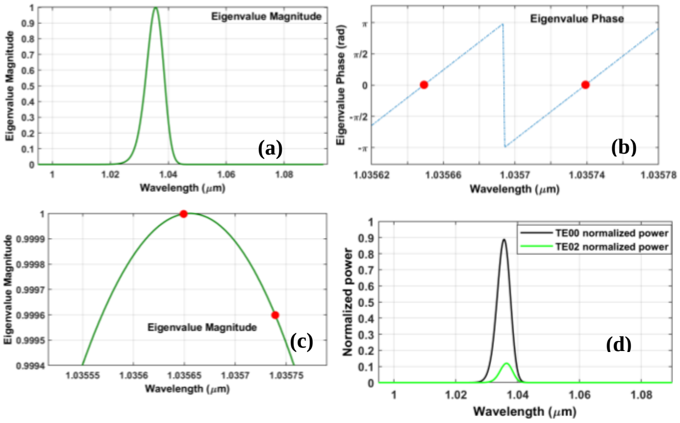

Table 1

Parameter	Description
$\tilde{\beta} = \frac{\beta_1(\lambda) + \kappa_{11}(\lambda) + \beta_2(\lambda) + \kappa_{22}(\lambda)}{2}$	
$\delta = \frac{\beta_1(\lambda) + \kappa_{11}(\lambda) - \beta_2(\lambda) - \kappa_{22}(\lambda)}{2} - l\frac{\pi}{\Lambda}$	Codirectional detuning parameter
$s(\lambda) = \sqrt{\delta^2(\lambda) + k_{12}(\lambda)k_{21}(\lambda)}$	
$\beta_1(\lambda)$, $\beta_2(\lambda)$	Unperturbed propagation constants
κ_{12} , κ_{21},$\kappa_{11}$and κ_{22}	Mutual and self-coupling coefficients
l	An integer for which $\beta_1 - \beta_2 \approx l\frac{2\pi}{\Lambda}$

Fig. 3. (a) Eigenvalue magnitude **(b)** Eigenvalue phase (points in red color have zero phase and a magnitude close to 1) **(c)** Eigenvalue magnitude around zero detuning wavelength (points in red color have eigenvalue phase of zero) **(d)** Eigenvector

3. Conclusion

We presented a semi-analytical model for electrically injected monolithic nano-ridge lasers. The interference created between the fundamental TE00 mode and the TEM02 mode resulted in a loss dip that enabled laser operation.

4. Acknowledgement

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3. Y. Shi et al., "Optical pumped InGaAs/GaAs nano-ridge laser epitaxially grown on a standard 300-mm Si wafer," Optica 4(12), 1468 (2017).
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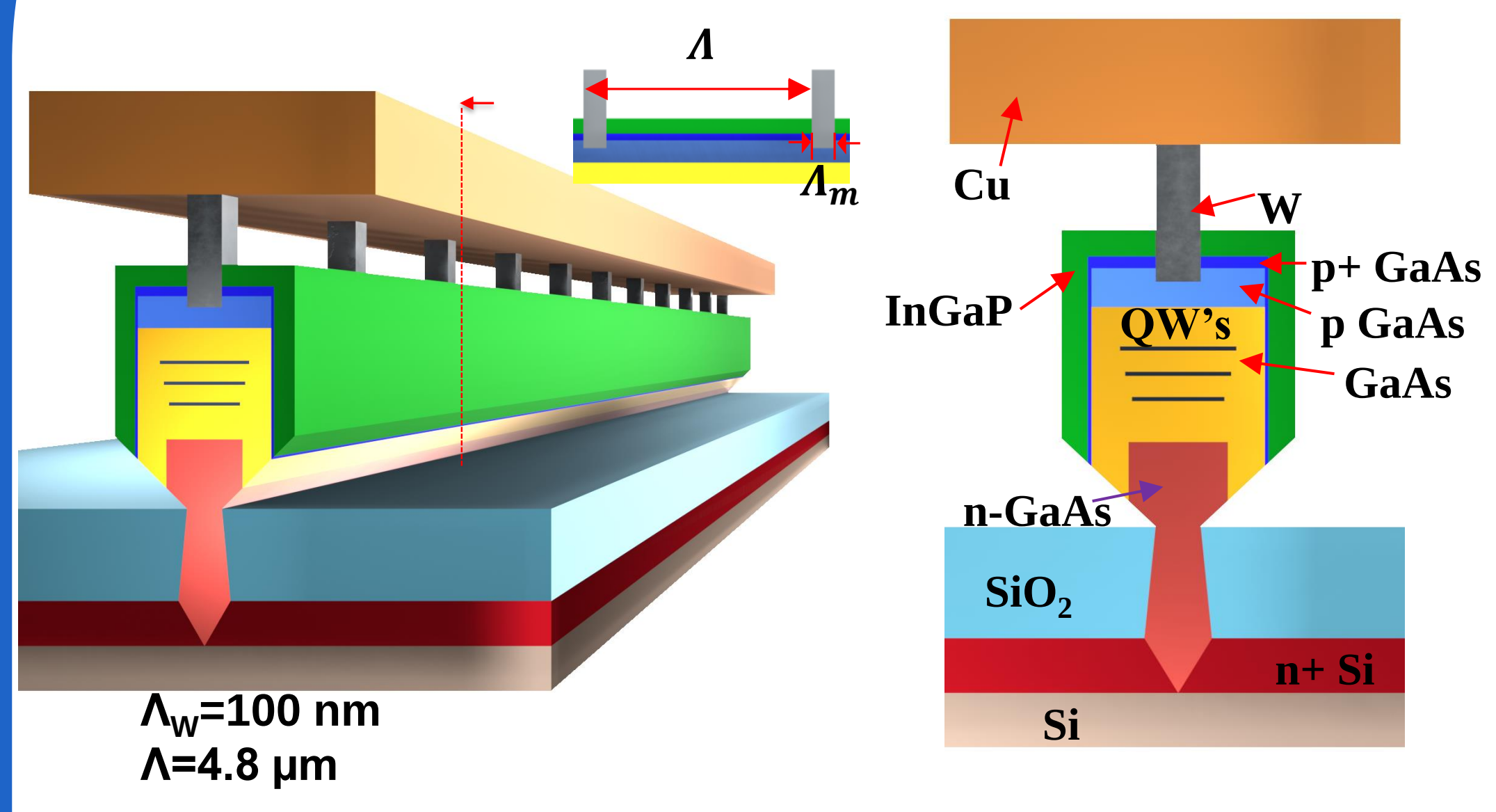
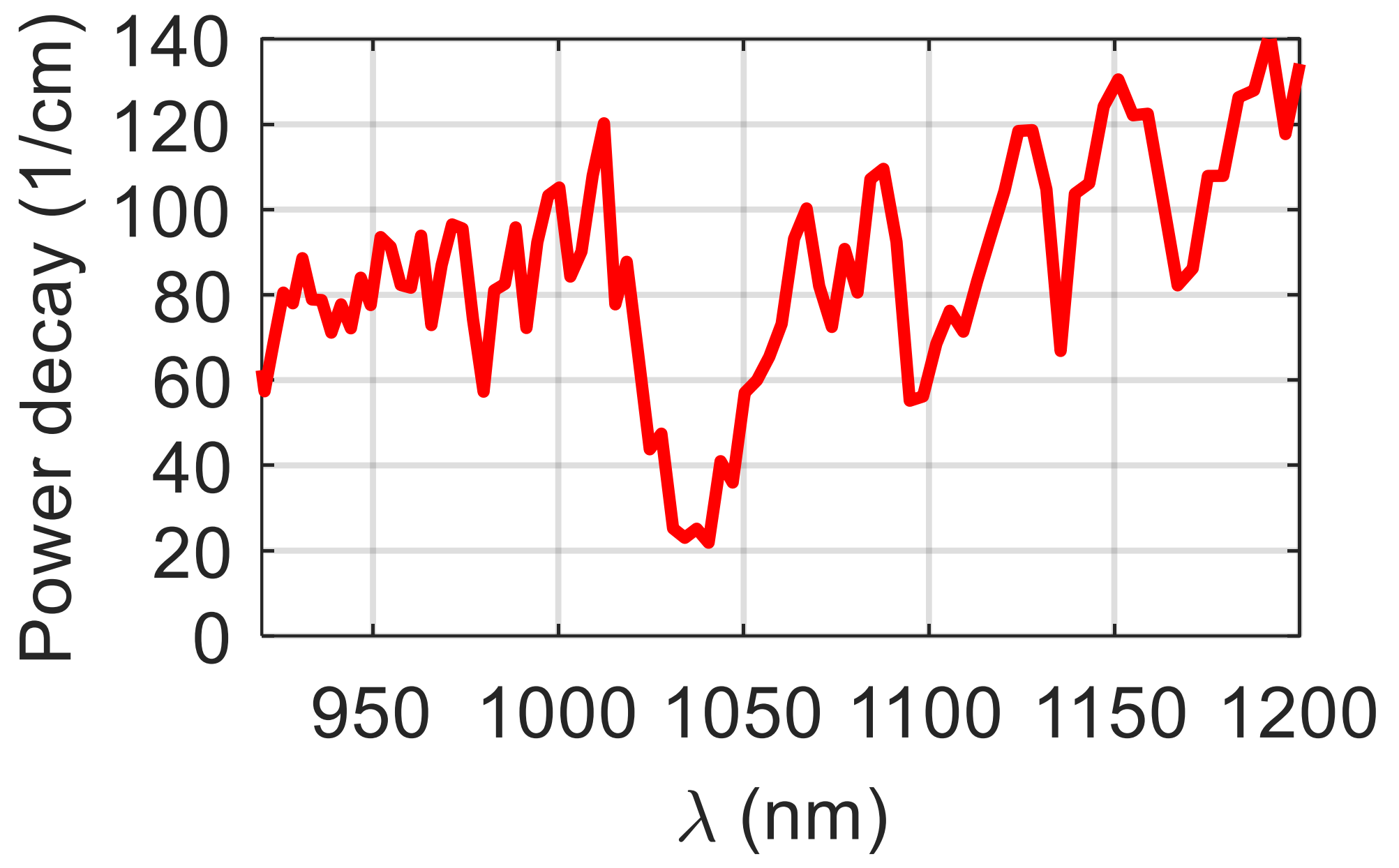
Introduction

Electrical pumping of our monolithic $In_{0.2}Ga_{0.8}As/GaAs$ multi quantum well lasers, fabricated by nano-ridge engineering, has so far proved very difficult [1]. Recently, it was successfully demonstrated exploiting a mode beating effect to reduce losses [2]. Here, we present an analytical model based on codirectional coupling which explains the results in [2] and allows further optimization of the devices in the future.

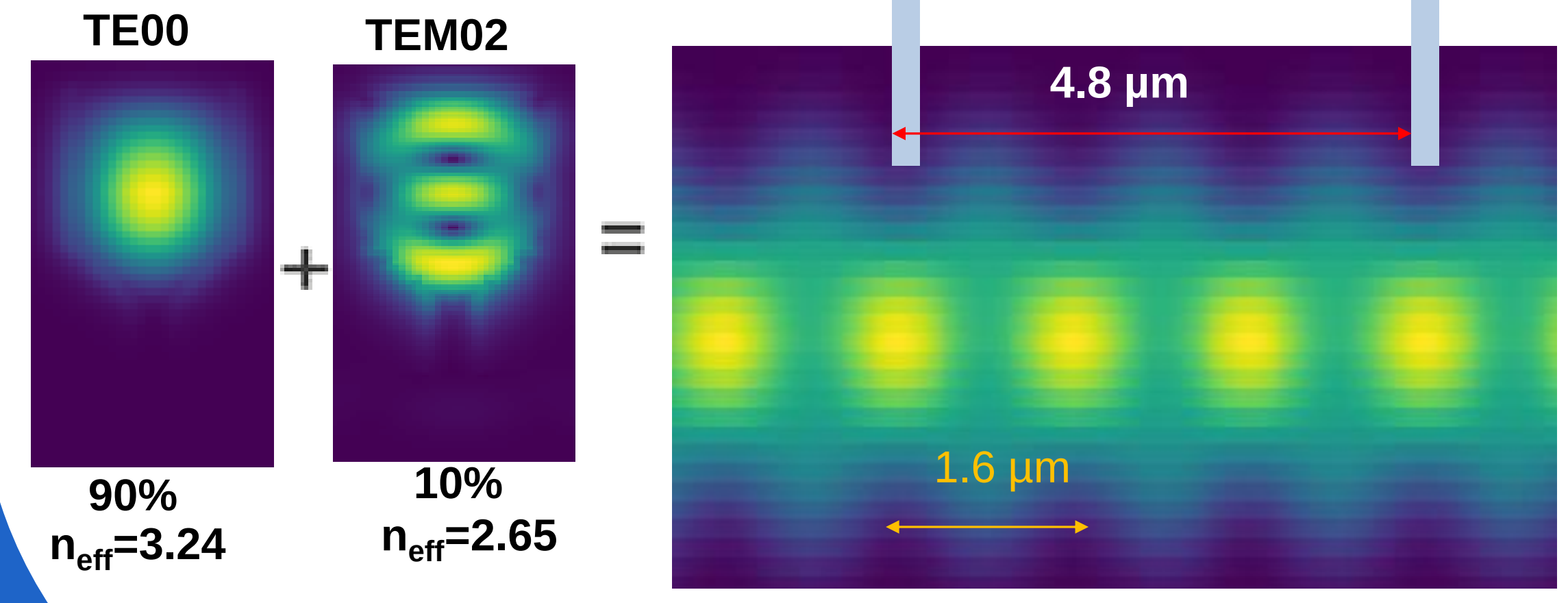
Codirectional Coupling in a nano-ridge waveguide (FDTD Simulation)



- Launching TE00 mode at z=0 and monitoring power in TE00 and TEM02 modes at z=50 μm and z=100 μm by Lumerical FDTD simulations

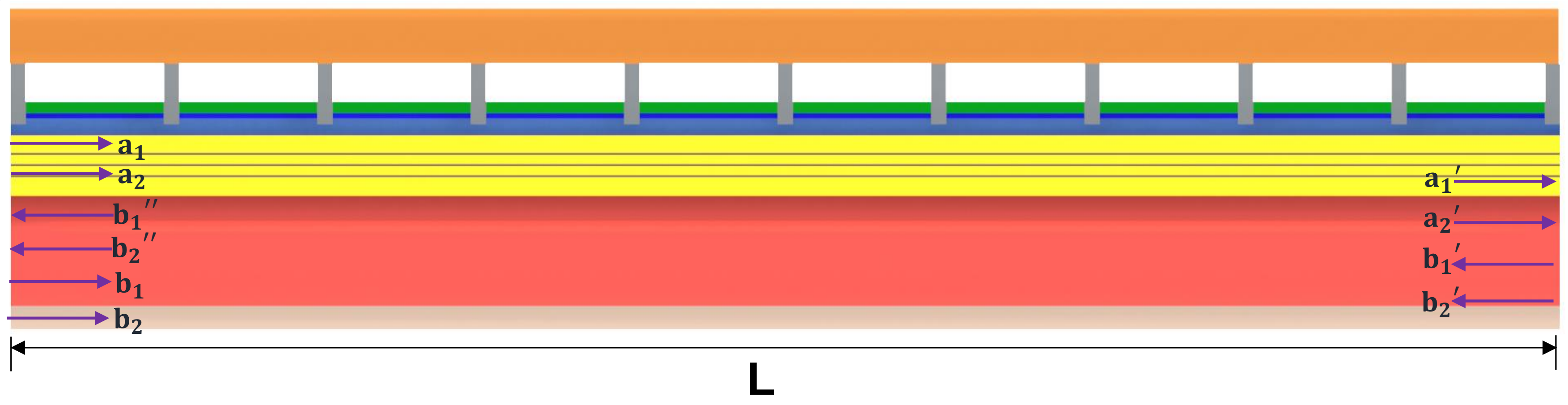


- Dip for the TE00 mode power decay around λ=1.035 μm allows laser operation.



- The dip around λ=1.035 μm is due to mode beating between the TE00 and TEM02 modes creating a pattern that makes contacts possible at lowest intensity regions.

Round-trip laser model



- Normalized amplitudes for TE00 and TEM02 modes in a round-trip:

$$\begin{bmatrix} \boldsymbol{b_1} \\ \boldsymbol{b_2} \end{bmatrix} = \boldsymbol{R.T.R.T.} \begin{bmatrix} \boldsymbol{a_1} \\ \boldsymbol{a_2} \end{bmatrix}$$

$$R = \begin{bmatrix} r_{11} & r_{12} \\ r_{21} & r_{22} \end{bmatrix}, \qquad T = \begin{bmatrix} (cos(sL) - j\frac{\delta}{s}\sin(sL))e^{-j\left(\tilde{\beta}+l\frac{\pi}{\Lambda}\right)L} & -j\frac{\kappa_{12}}{s}\sin(sL)\, e^{-j\left(\tilde{\beta}+l\frac{\pi}{\Lambda}\right)L} \\ -j\frac{\kappa_{21}}{s}\sin(sL)\, e^{-j\left(\tilde{\beta}-l\frac{\pi}{\Lambda}\right)L} & (cos(sL) + j\frac{\delta}{s}\sin(sL))e^{-j\left(\tilde{\beta}-l\frac{\pi}{\Lambda}\right)L} \end{bmatrix}$$

where $r_{11}, r_{12}, r_{21}, r_{22}$ are reflection coefficients.

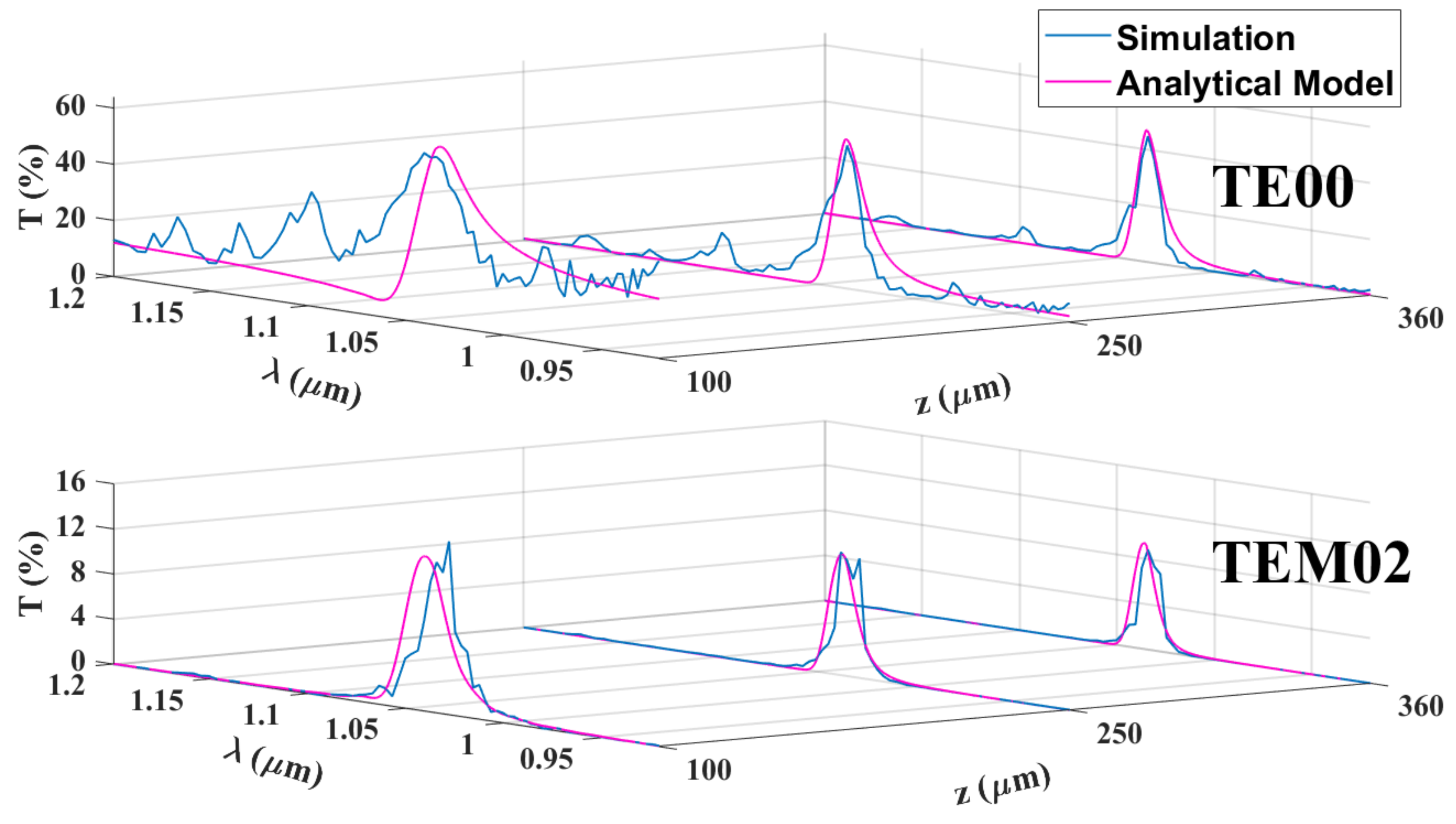
Codirectional Coupling in a nano-ridge waveguide (Analytical Expression)

- We derived the power in the modes by solving the coupled differential equations for the electric field of the modes and compared these results with FDTD simulation results.

$$P_1(z) = \left|\left(\cos(sz) - j\frac{\delta}{s}\sin(sz)\right)\right|^2 e^{-2Im(\tilde{\beta})z}$$ For the TE00 mode

$$P_2(z) = \left|\left(\frac{\kappa_{21}}{s}\sin(sz)\right)\right|^2 e^{-2Im(\tilde{\beta})z}$$ For the TEM02 mode

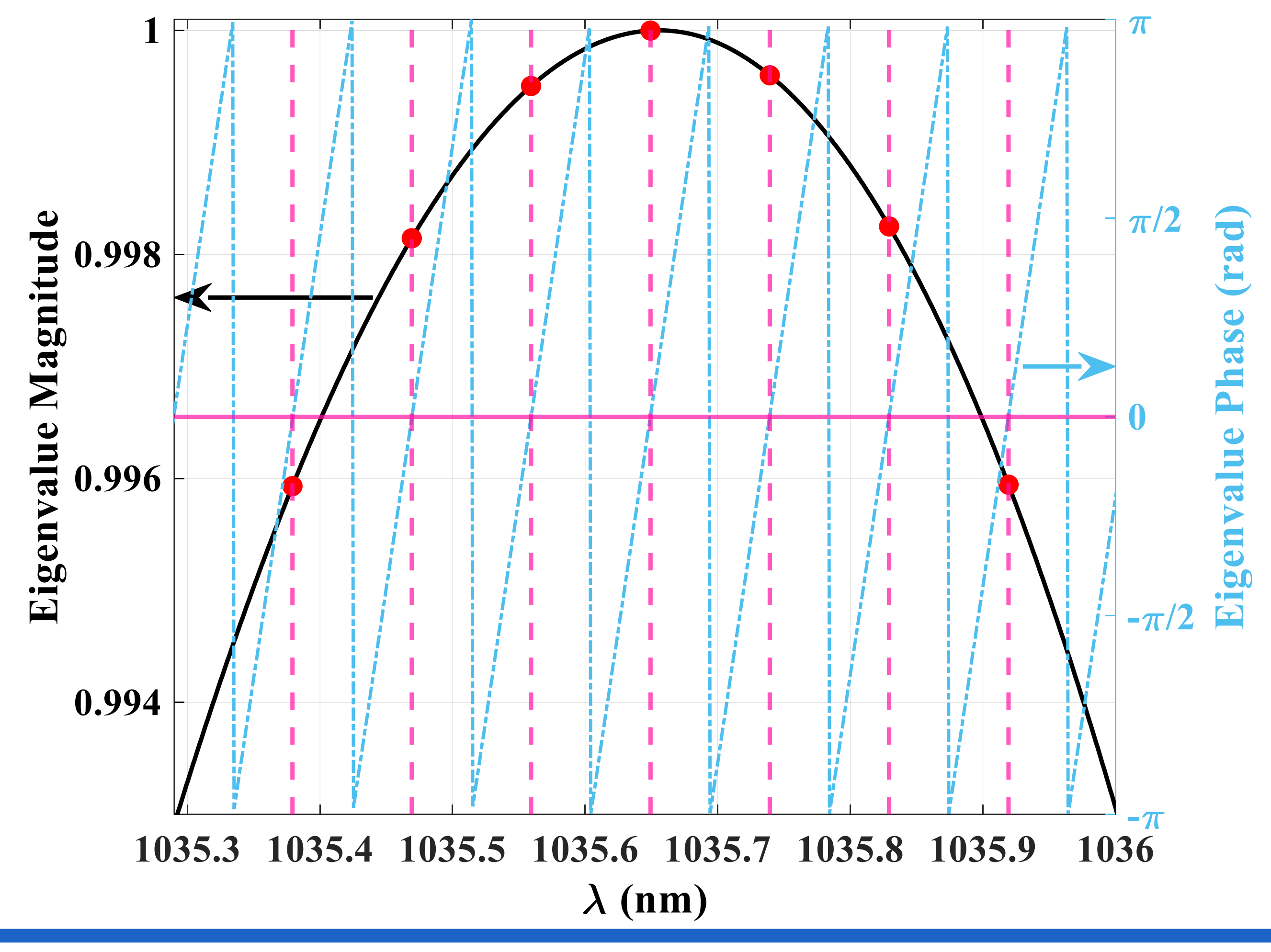
where $\tilde{\beta} = \frac{\beta_1+\kappa_{11}+\beta_2+\kappa_{22}}{2}$, $\delta = \frac{\beta_1+\kappa_{11}-\beta_2-\kappa_{22}}{2} - l\frac{\pi}{\Lambda}$ and $s(\lambda) = \sqrt{\delta^2 + \kappa_{12}\kappa_{21}}$



✓ **Very good agreement between model and simulations.**

Threshold Gain

- Lasing is obtained for an eigenvalue of 1 of the round-trip matrix.
- Calculated threshold gain is 792 cm^{-1} for a device length of 1502.4 μm.



For points in red color: Eigenvalue phase=0

Conclusion

We developed a laser model for electrically injected monolithic nano-ridge lasers that can be employed for efficient device optimization in the future.

References

1. Y. Shi et al., Optica 4(12), 1468 (2017).
2. Y. De Koninck et al., arXiv:2309.04473, (Sept. 2023).

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