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# Design of a Widely Tunable Laser with a Chirped Ladder Filter

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# Outline

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1. Background
2. Device structure
3. Design concept for wide tuning range
4. Numerical simulation of lasing spectra and tuning characteristics
5. Summary

# Background

## Widely tunable laser

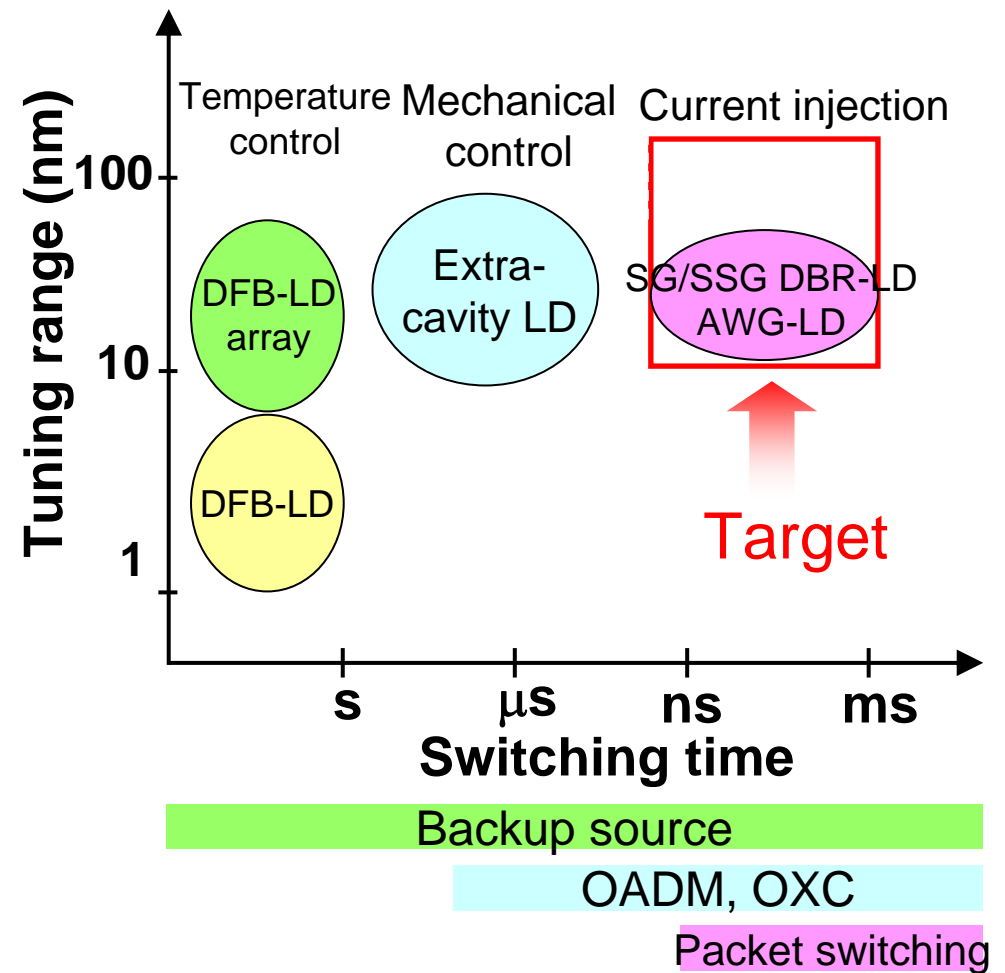
- SG-DBR-LD
- SSG-DBR-LD
- GCSR-LD
- Complex operation
- LD with AWG and SOAs (Digital wavelength tuning)
- Large size

## Our approach

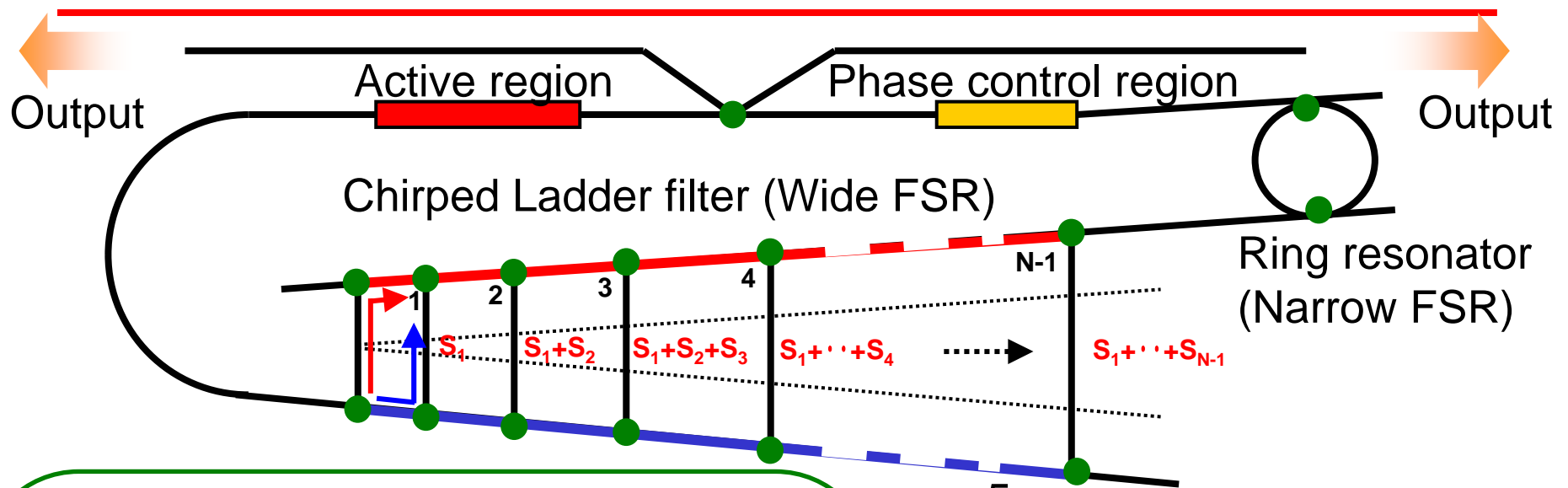
- Tunable ring laser with ladder filter and ring resonator

## Goal

- Tuning range of over 40 nm



# Device Structure

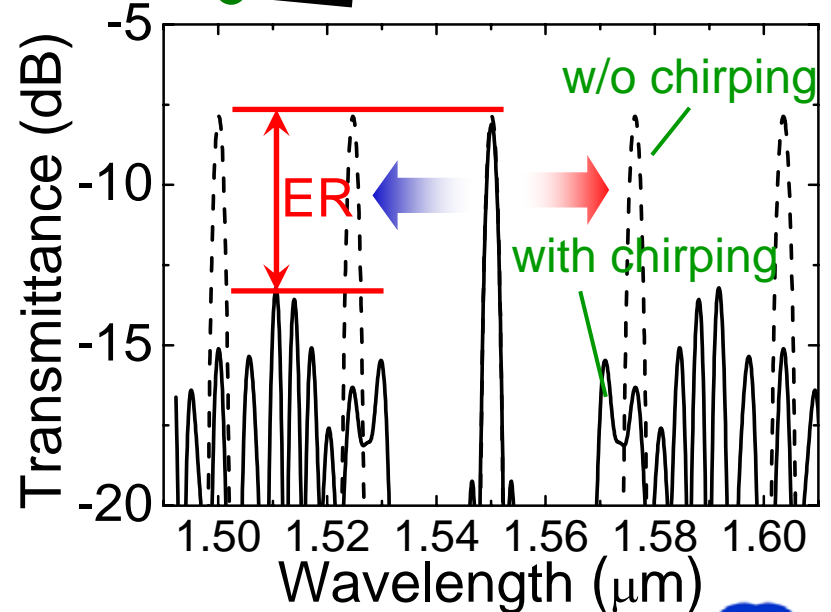


## Feature

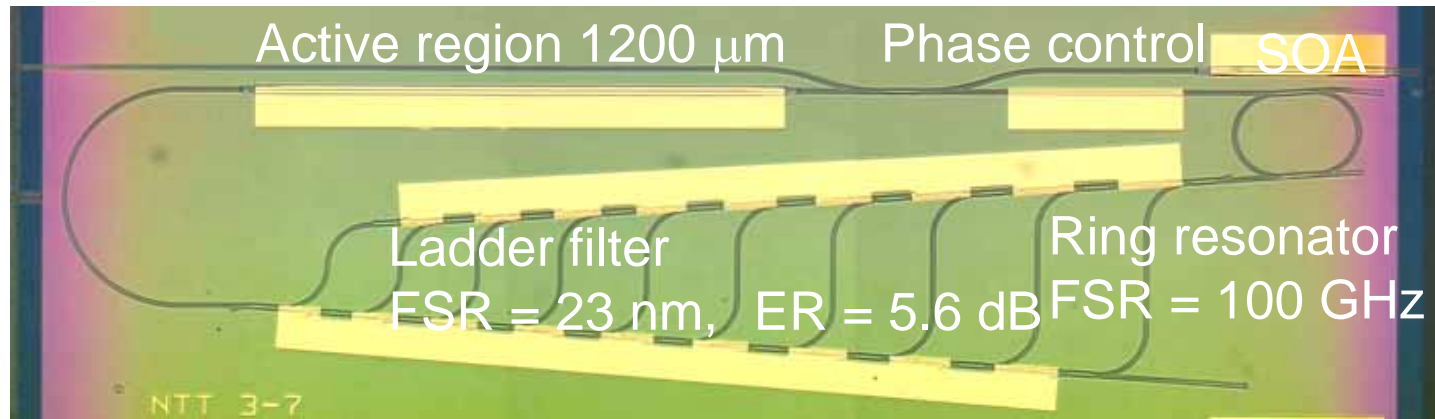
- Digital wavelength tuning  $\Delta\lambda = \frac{\Delta n_{eff} L_i}{m}$
- Suppression of unnecessary modes by chirping

$$S_k = m_k \lambda_0 / n_{eq}, \quad m_k = m_0 + \left(k - \frac{N}{2}\right) \gamma$$

$L_i$ : Length of electrode     $n_{eff}$ : Effective index  
 $m$ : Diffraction order         $\gamma$ : Chirping parameter



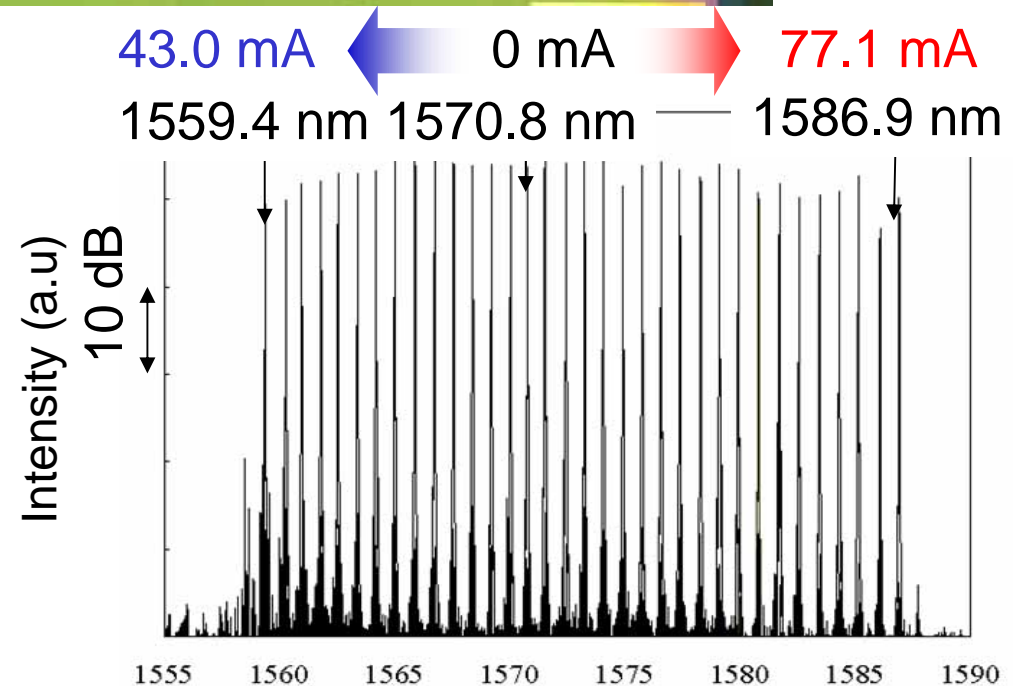
# Fabricated Device



- Active region: MQW, ridge  
 $w = 1.6 \mu\text{m}$ ,  $h = 1.8 \mu\text{m}$
- Waveguide region:  
 Deep ridge (1.4Q)  
 $w = 1.6 \mu\text{m}$ ,  $h = 3.5 \mu\text{m}$
- Size: 3.2 x 1.0  $\text{mm}^2$

Tuning range ( $\Delta\lambda_c$ ) 27 nm  
 spacing 100 GHz

Design for  $\Delta\lambda_c > 40 \text{ nm}$ ?

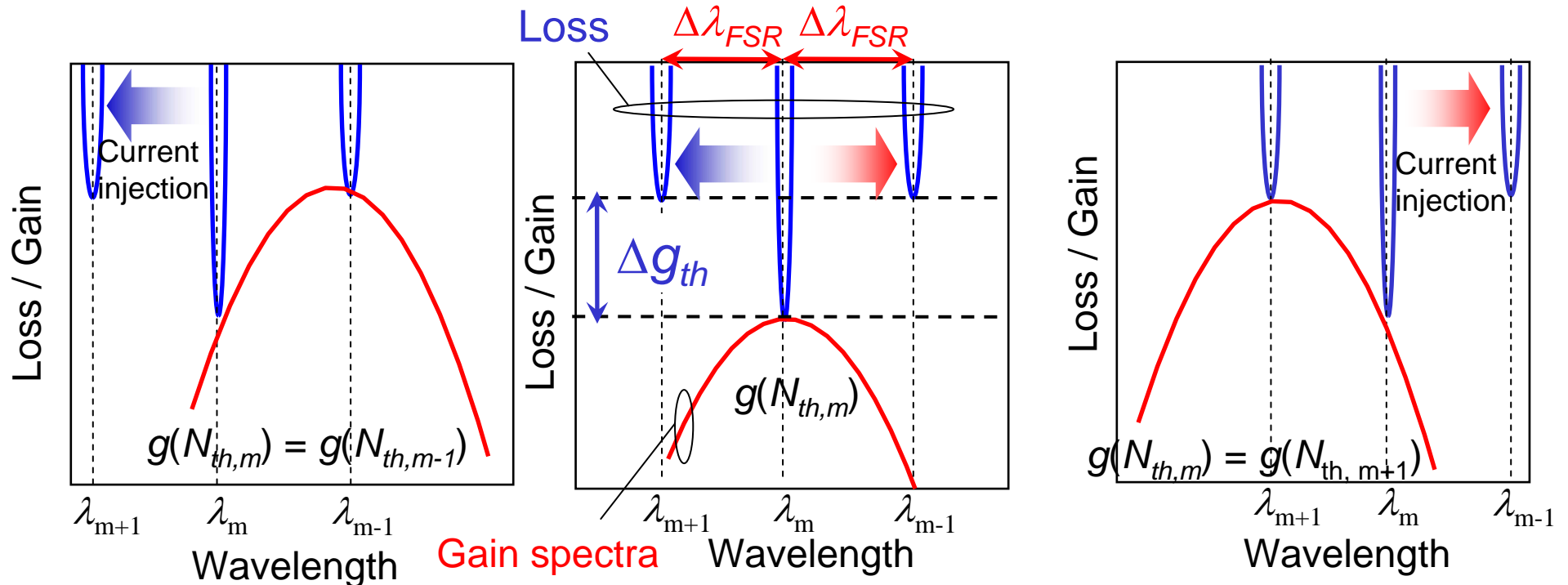


# Conditions for Lasing in Central Mode <sup>6</sup>

$$\lambda = \lambda_{cmin}$$

$$\lambda_{cmin} < \lambda < \lambda_{cmax}$$

$$\lambda = \lambda_{cmax}$$



## Lasing conditions for central mode

$$N_{th,m} < N_{th,m-1}$$

$$N_{th,m} < N_{th,m+1}$$

$N_{th,m}$ : Threshold carrier density

## Tuning range

$$\Delta\lambda_c = \lambda_{cmax} - \lambda_{cmin}$$

# Analytical Expression for Tuning Range

## Gain spectra

$$g = g'_N (N_c - N_0) - \frac{g''_\lambda}{2} (\lambda - \lambda_p)^2$$

## Gain peak wavelength

$$\lambda_p = \lambda_{p0} - \lambda'_p N_c$$

## Wavelength of transmittance peak

$$\lambda_{m+1} = \lambda_m - \Delta\lambda_{FSR}$$

$$\lambda_{m-1} = \lambda_m + \lambda_{FSR}$$

## Threshold gain coefficient

$$g_{th,m+1} = g_{th,m-1} = g_{th,m} + \Delta g_{th}$$

- $g$ : Gain coefficient
- $N_c$ : Carrier density
- $N_0$ : Transparent carrier density
- $\lambda$ : Wavelength
- $\lambda_p$ : Gain peak wavelength
- $\lambda_{p0}$ : Bandgap wavelength
- $g_{th}$ : Threshold gain
- $m$ : Diffraction order

$\Delta g_{th}$ : Difference in threshold gain due to chirped structure

## Lasing conditions for central mode

$$N_{th,m} < N_{th,m-1}$$

$$N_{th,m} < N_{th,m+1}$$



## Tuning range

$$\Delta\lambda_c = \Delta\lambda_{FSR} + \frac{2\Delta g_{th}}{g''_\lambda \Delta\lambda_{FSR}}$$

# Requirements for Wide Tuning Range <sup>8</sup>

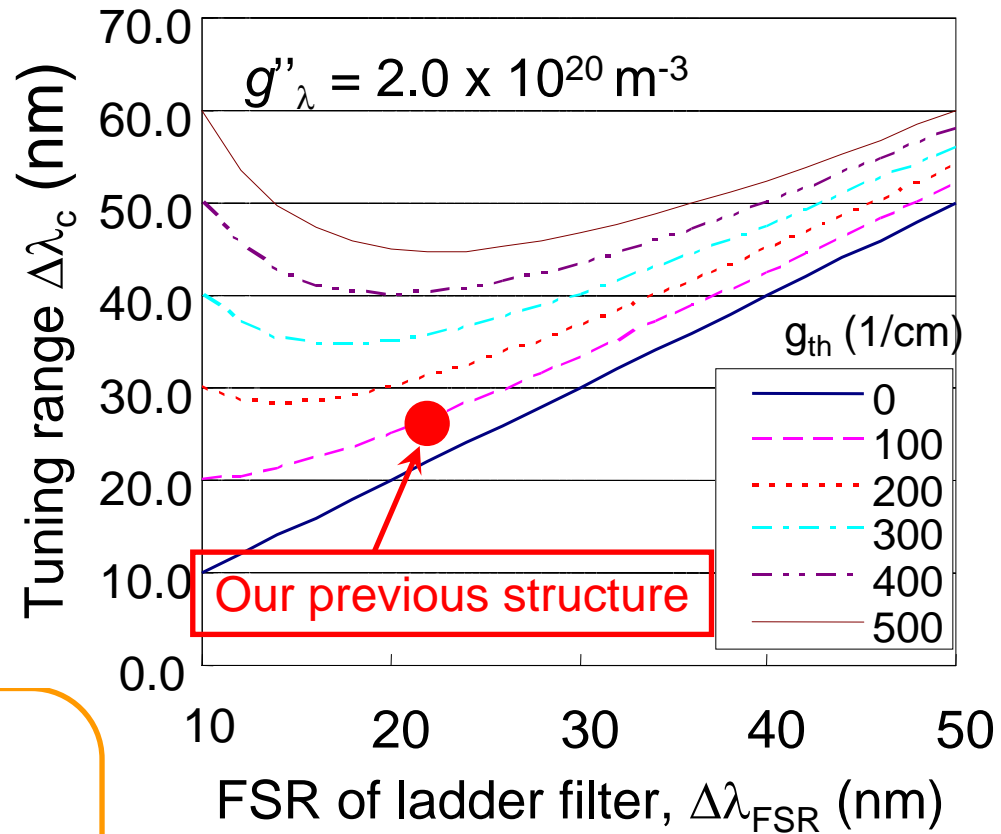
Tuning range

$$\Delta\lambda_c = \Delta\lambda_{FSR} + \frac{2\Delta g_{th}}{g''_{\lambda} \Delta\lambda_{FSR}}$$

Effect of chirping

No chirping

- Expansion of tuning range
- Large FSR of ladder filter
  - Small  $g''_{\lambda}$  (Flat gain spectrum)
  - Large  $\Delta g_{th}$  (Extinction ratio of ladder filter)



Is large FSR sufficient condition?

# Design of Ladder Filter

FSR of ladder filter (no chirping)

$$\Delta\lambda_{FSR} = \frac{n_{eff} \Delta S}{m(m+1)} \approx \frac{\lambda_0}{m+1}$$

3-dB bandwidth of ladder filter

$$\Delta\lambda_{3dB} \propto \frac{1}{mN}$$

$n_{eff}$ : Effective index

$m$ : Diffraction order

$\Delta S$ : Difference of optical path

$\lambda_0$ : Central wavelength

$N$ : Number of ladders

Ref. S. -H. Jeong et al., Appl. Opt., 28, p6007, 2005.

Large FSR



- Large 3-dB bandwidth
- Mode selectivity is degraded

Chirping is necessary to expand tuning range

# Design of Laser Structure

## Tunable region

$$\Delta\lambda_c = \Delta\lambda_{FSR} + \frac{ER}{10\log_{10}(e)\Gamma L} \frac{2}{g_\lambda'' \Delta\lambda_{FSR}}$$

$\Gamma$ : Optical confinement

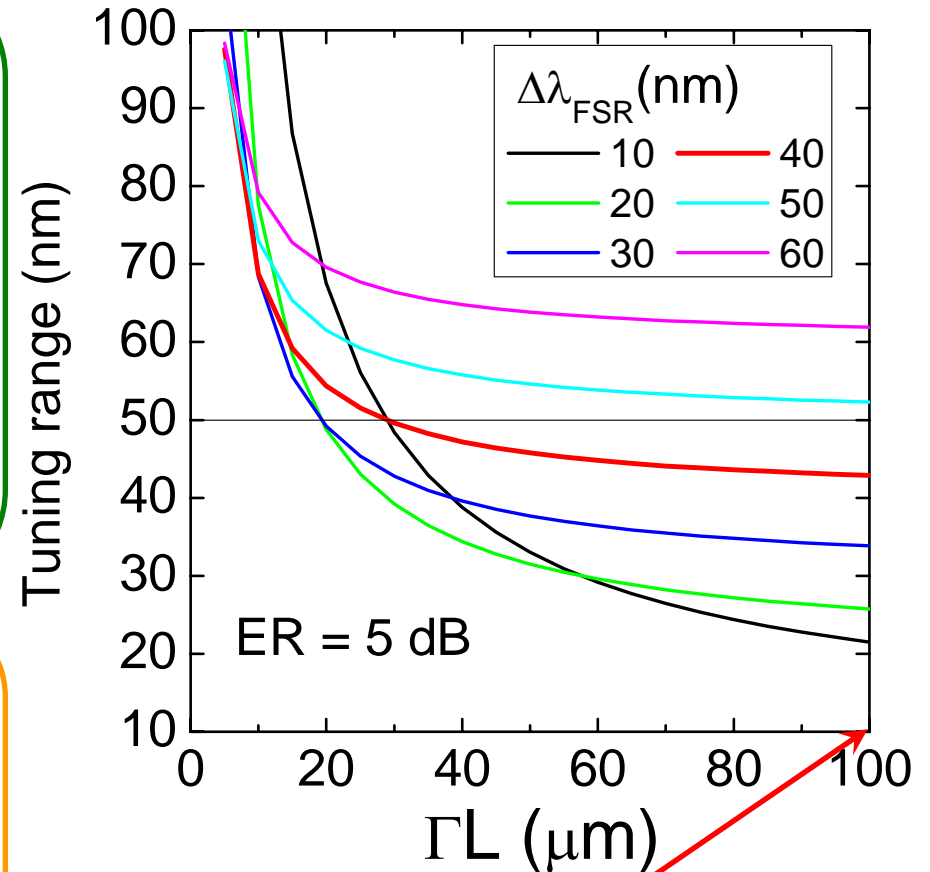
$L$ : Length of active layer

$ER$ : Extinction ratio of ladder filter (dB)

## Approach

- Large extinction ratio of ladder filter ( $ER$ ) induced by chirped structure
- Flat gain spectra (small  $\Gamma L$ )

➔ Full C, L-band (40 nm) operation

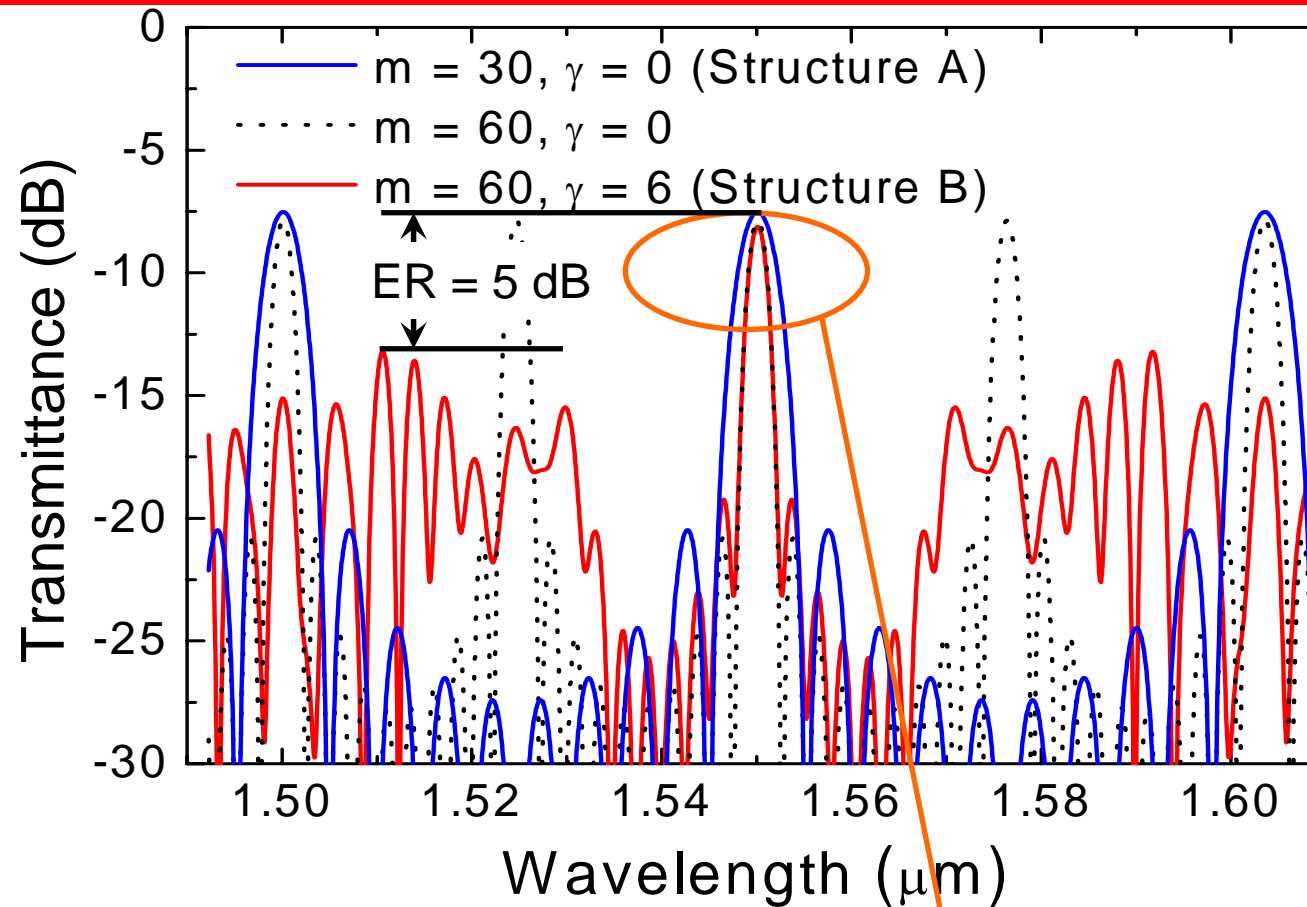


Our structure

$$\Gamma = 0.08$$

$$L = 1200 \mu\text{m}$$

# Transmission Spectrum of Ladder Filter



## Structure

A: Without chirping ( $\Delta\lambda_{\text{FSR}} = 50 \text{ nm}$ )

B: With chirping ( $\Delta\lambda_{\text{FSR}} = 40 \text{ nm}$ )

$$\Delta\lambda_{3\text{dB}}(\text{A}) > \Delta\lambda_{3\text{dB}}(\text{B})$$



$$\text{MSR}(\text{A}) < \text{MSR}(\text{B})$$

# Multimode Rate Equation Model

## Quantitative simulation

- Tuning range
- Lasing spectra
- Mode suppression ratio (MSR)



## Multimode rate equation model

Including

- Gain spectrum
- Transmittance spectra (ring, ladder filter)

## Rate equations

$$\frac{dS_i}{dt} = \left( G_i - \frac{1}{\tau_{pi}} \right) S_i + \frac{\beta}{\tau_r} N_c$$

$$\frac{dN_c}{dt} = \frac{I}{eV} - \sum_i G_i S_i - \frac{N_c}{\tau_r}$$

$S_i$ : Photon density

$\tau_p$ : Photon lifetime

$\tau_r$ : Carrier lifetime

$G$ : Optical gain

$N_c$ : Carrier density

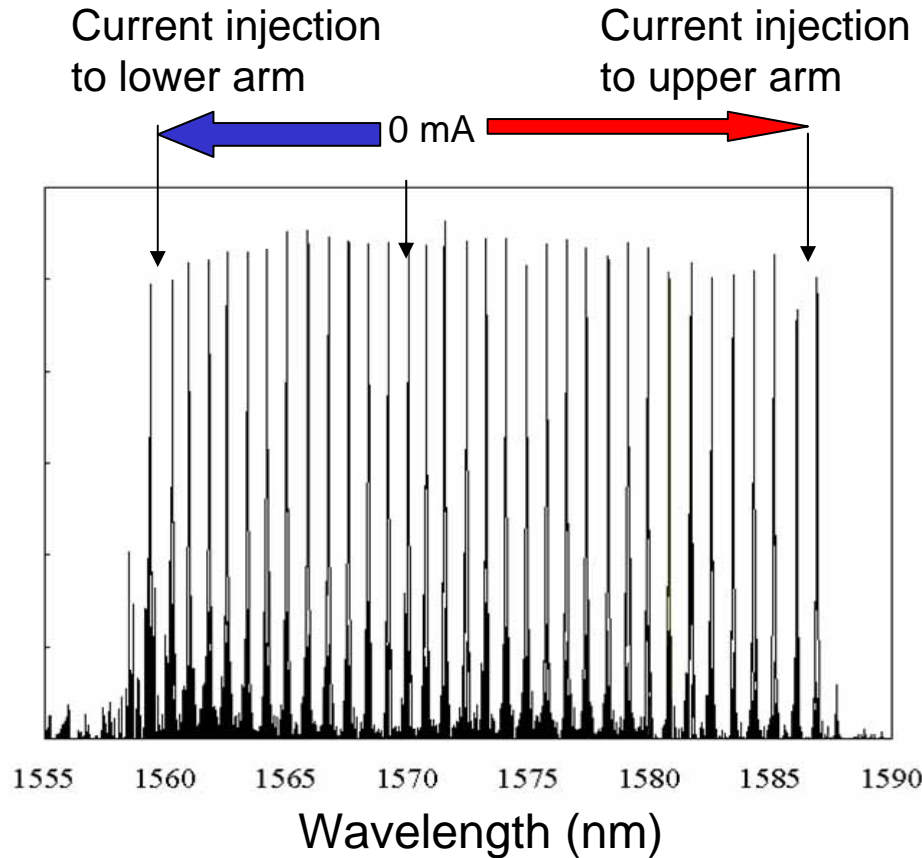
$I$ : Current

$V$ : Volume of active layer

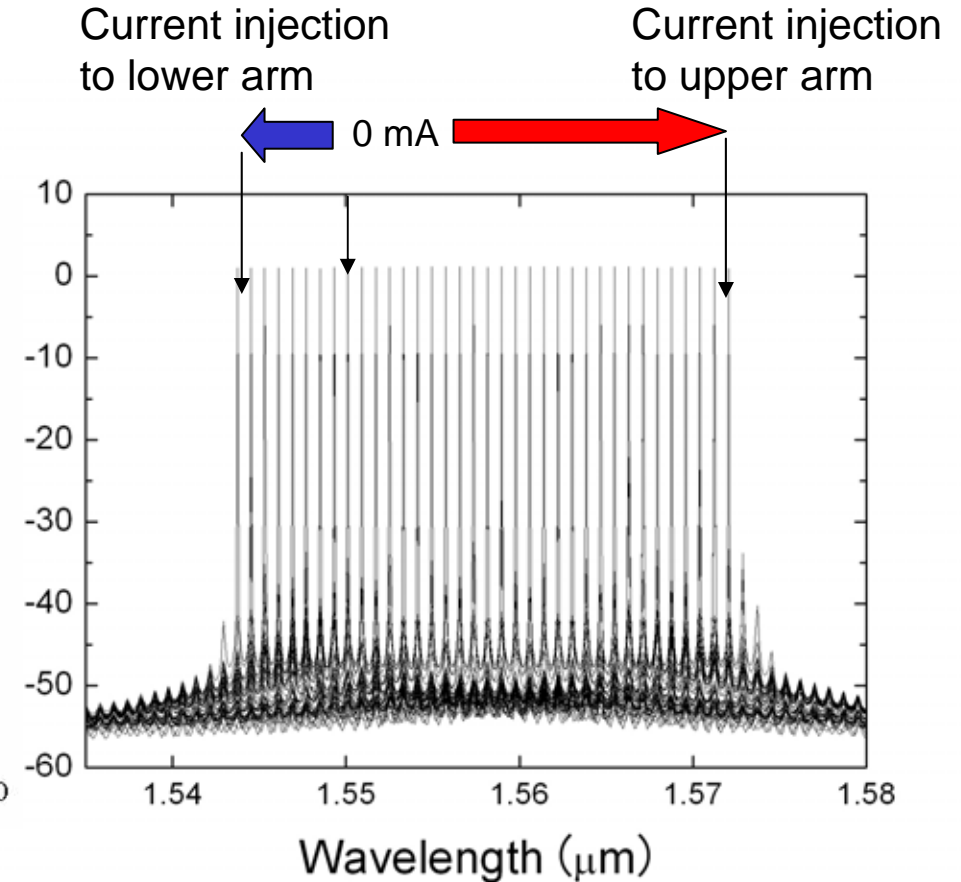
$i$ : Mode index

# Lasing Spectra

## Experiment

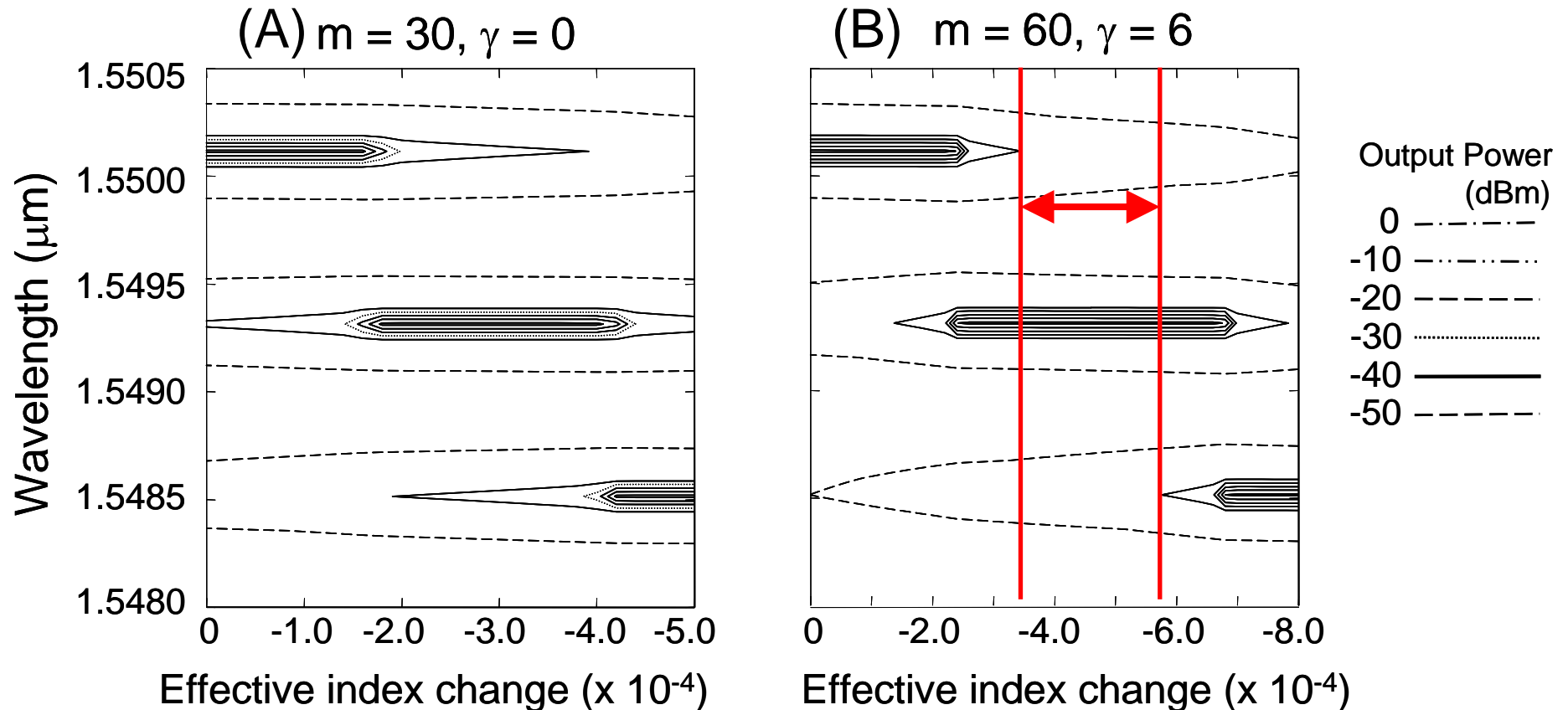


## Simulation



- Digital tuning by current injection with spacing of 100 GHz
- Tuning range of 27 nm

# Effect of Chirping – Improvement of MSR<sup>14</sup>



Without chirping

- $\Delta\lambda_c = 50$  nm
- MSR < 40 dB

With chirping

- $\Delta\lambda_c = 46$  nm
- MSR > 40 dB

# Summary

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- Design of tunable laser with chirped ladder-type filter and ring resonator for wide tuning range
- Expansion of tuning range
  - Wide FSR of ladder filter
  - Chirped ladder structure
  - Flat gain spectrum
- Effect of chirped structure
  - Wide tuning range and stable lasing ( $\Delta\lambda_c > 40$  nm)
  - High mode suppression ratio ( MSR > 40 dB)