Direct Visualization of the In–Plane Leakage of High–Order Transverse Modes in VCSELs Mediated by Oxide–Aperture Engineering

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Outline

- Motivation for Single Mode VCSELs
- Leaky VCSELs
  - Concept
  - Modeling
  - Experiment
- Benchmarking to conventional VCSELs
- Modeling of additional processing steps
  - Oxide-relief
  - Zinc-intermixing
- Conclusion
Single Mode VCSELs

Used in Datacom & Sensing

Benefits:

- \(<< 0.1 \text{ nm FWHM} – \text{no dispersion}\)
  Long transmission distance - \(54 \text{Gbps} \) 2.2 km

- **Low noise**
  No mode partition noise
  Noise is smaller
  (important for 4-PAM)

- Suitable for
  Wavelength Division Multiplexing (WDM)
Motivation for Single Mode VCSELs

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  • Concept
  • Modeling
  • Experiment

Benchmarking to conventional VCSELs

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Conclusion
Leaky VCSEL Structure

Improved Single-Mode emission through leakage of high order modes

- High order modes have intensity maxima close to the aperture boundary.
- One can generate a new mode in the periphery with a high overlap integral with the VCSEL mode and enable the leakage.
Leakage via additional cavities

Active cavity & second cavity modes have different number of nodes (field polarity reversal)

Second cavity mode in oxidized periphery – is non-orthogonal to the VCSEL mode and has 30% overlap

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The 3D simulations of electromagnetic fields

**Model:**
Finite element software package based on full vector Maxwell’s equations

Rotationally symmetric

**Software:**
VIS VCSEL Software + JCM Wave + Matlab

→ **Fundamental mode:** lower leakage loss
→ **Higher order modes:** higher leakage loss

3D modeling is in agreement with 1D modeling.

Leaky emission escapes crystal at 35° degrees.

Lateral leakage: coupling of VCSELs with other VCSELs or monitor PDs (single wafer w. lasers as PDs)

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In-house characterization at VIS:
- DC optical characterization
- High-frequency testing
- Near-field imaging
- Far-field imaging

- Infrared (IR) imaging (for determination of oxide apertures)
- Accelerated Ageing
- Full wafer mapping
Leaky VCSEL ~5µm aperture: narrow spectrum, fundamental mode first

In this particular case:
Both designs with higher amount of DBR pairs
Internal losses dominate over external losses.
25Gb eye 6mA with 0.3mV peak-to-peak modulation (PRBS7)
Leaky VCSELs different oxide apertures

Conventional VCSEL ~5µm aperture: 30° beam divergence, donut mode first
Leaky VCSELs different oxide apertures

**Conventional VCSEL ~5µm aperture:** 30° beam divergence, donut mode first

**Leaky VCSEL ~5µm aperture:** single mode up to 2mA
Leaky VCSELs different oxide apertures

Leaky VCSEL ~5µm aperture: single mode up to 2mA

Leaky VCSEL ~4.5µm aperture: single mode up to 4mA (leakage stronger)
3D Modeling: Parameters

Mode distance between the **Fundamental** and the **Excited mode** is connected to the oxide aperture diameter.

**Leakage strength** is connected to the lifetime selection of the **Fundamental** and the **Excited Mode** (Ratio of lifetimes).

**Temperature effects** should be included in the modeling.
3D Modeling: Parameters

Mode distance between the **Fundamental** and the **Excited mode** is connected to the **oxide aperture diameter**

**Leakage strength** is connected to the lifetime selection of the **Fundamental** and the **Excited Mode** (Ratio of lifetimes)

**Temperature effects** should be included in the modeling

- **✓** Aperture diameter confirmed by IR imaging
- **✗** Leakage oscillates with the aperture diameters *(aperture size is technically hard to control)*

Room for improvement & 3D modeling can help during design phase
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**Oxide relief**: replace oxide apertures with air

Decrease mechanical stress in the structure, higher refractive index step

Excited mode in conventional VCSEL: high angle titled lobes, increased mode lifetime ratio ✓
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**Zn diffusion:** Impurity intermixing of top-DBR of the VCSEL
Leakage of high-order modes.

Zn-diffusion in leaky VCSELs

Oxide apertures - 6µm

- In-plane leakage is eliminated
- New type of leakage into the Intermixed area occurs
Zn Diffusion

Far-field profiles

- **Fundamental mode**
- **Excited mode**

**Without Zn-diffusion**

Leakage lobes as seen before

**With Zn-diffusion**

Leakage lobes disappear

Different leakage mechanism
Zn Diffusion

Zn destroys leakage through second cavity, but induces different leakage mechanism that also results in SSR and SM operation. ✓

Single mode possible through exclusively Zn-diffusion without oxide apertures will be modeled in the future.
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Conclusion

Leaky VCSELs:

- Accurate modeling of the leakage
- Experimental observation of the optical leakage

- Single mode emission — longer transmission distance
- Smaller beam divergence — better optical coupling
- Option of phase coupled arrays — beam steering
- Coupling of VCSEL with PD on wafer
- Confirmed high-frequency operation up to **100Gbps** error-free in DMT 300 m MMF

Comparison of 100m transmission capacity and possible up-scaling for discrete multitone (DMT) (SPIE 9766, 9766-19 Tomorrow Room 308 2:20 PM)
Thank You!

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