VERTICAL CAVITY LASERS FOR ATOMIC TIME STANDARDS

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Abstract

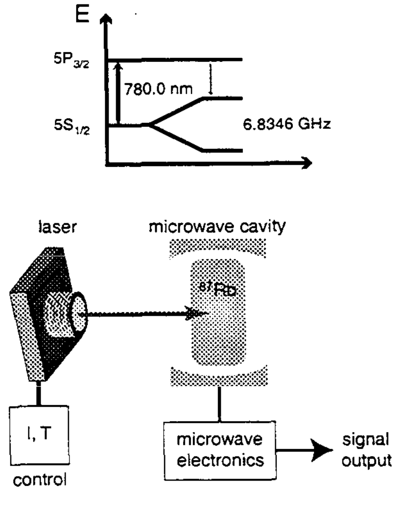
The availability of Vertical Cavity Lasers (VCSELs) has allowed the development of new generations of optical systems, which can benefit from the small size, low power consumption, and high reliability of these light sources. Among diode laser families, VCSELs are particularly attractive for a number of reasons: (1) relatively simple and robust fabrication; (2) very low threshold current and, thus, low power consumption; (3) surface emission, thus simplified packaging and two-dimensional array capabilities; (4) circular emission apertures and, thus, good beam shape in the near and far-field; and (5) single-mode emission with a high wavelength tuning rate and range.

Rubidium- or cesium-based atomic time standards could benefit greatly from the use of customized VCSELs as a pump for Rb or Cs. Required is a high spectral purity coupled with emission at precisely the pump wavelengths of interest: 780 or 852 nm. The Swiss Center for Electronics and Microtechnology (CSEM) has developed VCSELs for atomic time standard applications, which fulfill these requirements, and is preparing their industrialization. Optimized laser parameters include single-mode emission with a high side-mode suppression ratio, polarization stability, narrow linewidth, high tunability, and low noise. In this paper, we will discuss the principles underlying VCSEL operation, the required fabrication technology, and, finally, the electro-optical characteristics as these relate to the use of VCSELs in atomic clocks.

We will present device results on 780 nm VCSELs customized for operation at elevated temperatures for use in Rb time standards. An emphasis will be placed on spectral properties, tunability, and stability. Based on these developments, it is expected that VCSELs may soon play a significant role in a new generation of compact atomic time standards.

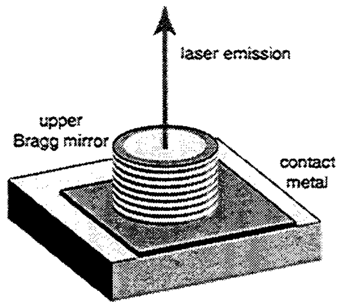
Lasers for atomic clocks

- Optical pump source for Rb or Cs
- VCSEL features
  - Compact
  - Low power
  - High efficiency
- System features
  - Small size
  - Low power



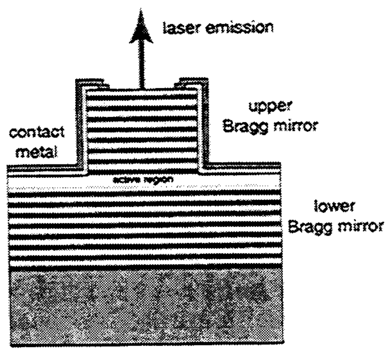
Why VCSELs ?

- Surface emission
- Circular beam profile
- Low threshold current
- Single longitudinal mode
- Narrow linewidth
- On-wafer testing
- Low cost potential



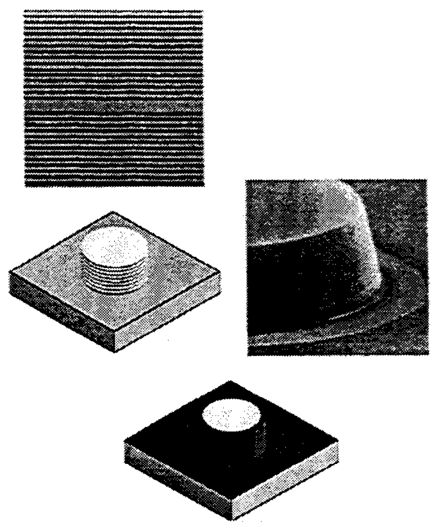
VCSEL: structure

- Vertical laser cavity
- Bragg mirrors
  - Epitaxially grown
  - Wavelength selective
- Emission wavelength
  - Gain & cavity overlap
  - Defined during growth
- Etched laser mesa



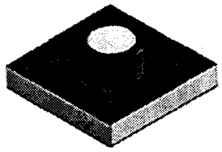
Fabrication I

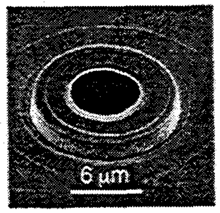
- Epitaxy
  - Mirror growth
  - Active region growth
- Mesa etch
  - Lateral definition
- Dielectric
  - Surface passivation
  - Aperture opening

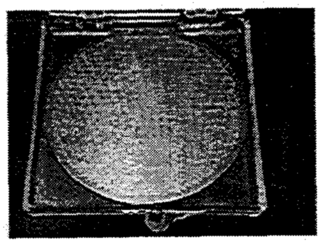


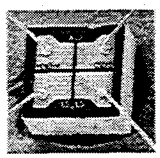
Fabrication II

- Metallization
  - Front & back-side
- 2” wafer
  - 6,800 VCSELs
- Separation
  - Cleave
  - Saw
- Packaging
  - TO cans or chips



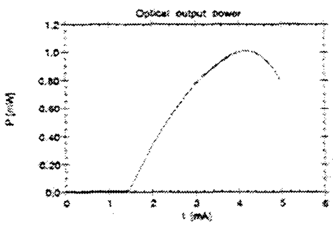


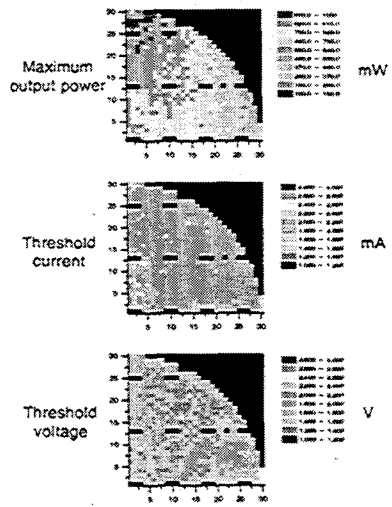




Basic characterization

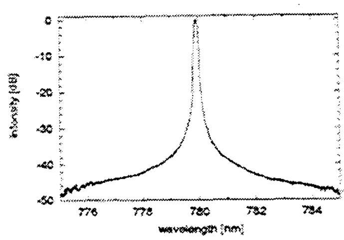
- Electro-optical maps
  - P vs I
  - I_{th} & V_{th}
  - Fully automated

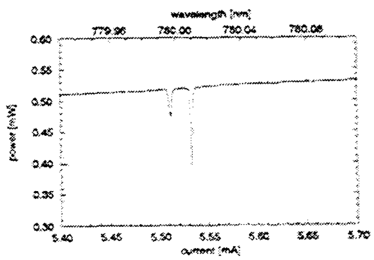




Spectrum

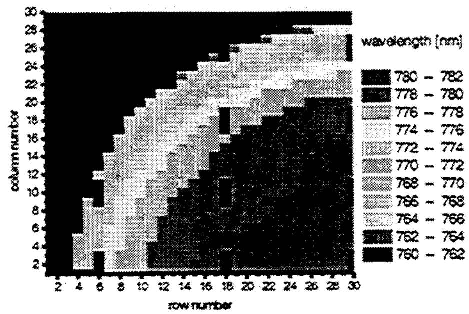
- $\lambda = 780.0$ nm
  - Room temperature
  - 70° by design
- Tuning
  - Current
    - 0.05 - 0.5 nm / mA
  - Temperature
    - 0.6 nm / °C
- Single longitudinal mode





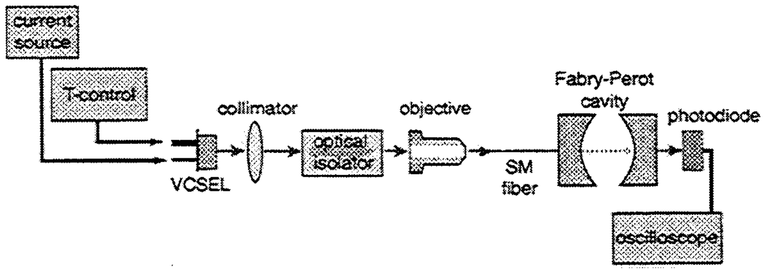
Wavelength uniformity

- Wavelength map
  - Automated testing
  - 1 nm resolution
- Non-uniformity
  - edge effects
  - Process effects
- Yield
  - f (required $\Delta\lambda$)



Linewidth I

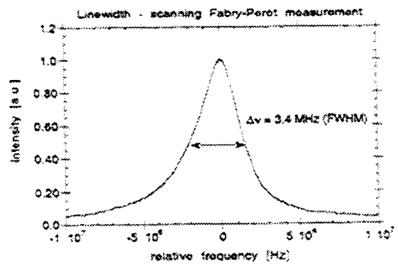
- Scanning spherical mirror Fabry–Perot
- Resolution: $\Delta\nu$ < 600 kHz
- AR–coated collimator: feedback « 1 nW



Scanning FP linewidth

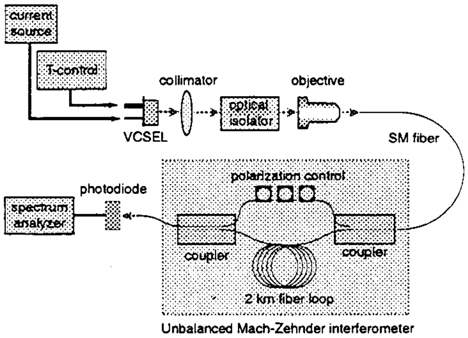
- Low–noise I–source:
  - RIN < 10^{-14} Hz^{-1}
  - I_{noise} < 0.6 nA/$\sqrt{Hz}$
- I = 5.4 mA
- T = 25° C
- $\Delta\nu = 3.4 \pm 0.6$ MHz

(average of 100 measurements)



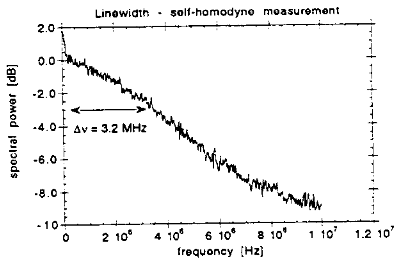
Linewidth II

- Delayed self–homodyne interferometer
- 2 km SM fiber delay line
- Resolution: $\Delta\nu < 100$ kHz



Self–homodyne linewidth

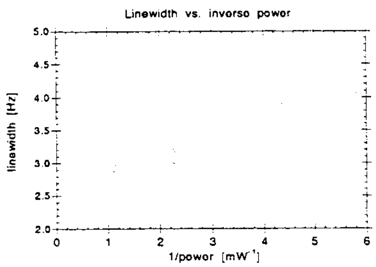
- Lorentzian curve fit
- Same low–noise current source



- I = 5.4 mA
- T = 25° C
- $\Delta\nu = 3.2$ MHz

Linewidth vs. power

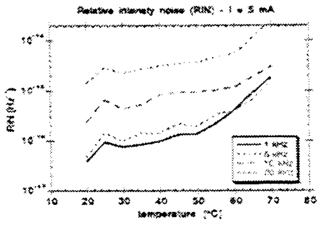
- Plot $\Delta\nu$ vs. 1/P

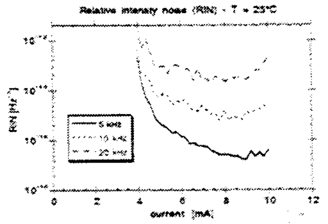


- Residual linewidth
  - ~ 2.4 MHz
- Linewidth•P product
  - ~ 305 kHz•mW

Noise

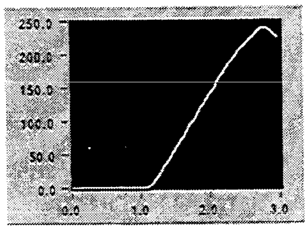
- Detector:
  - NEP < 31 pw/√Hz
- RIN(T) at I = 5 mA
- RIN(I) at T = 25°C
- Additional factors
  - Polarization stability

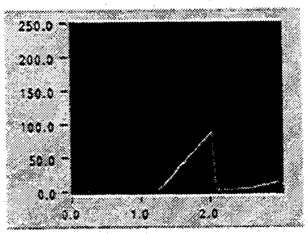




Polarization stability

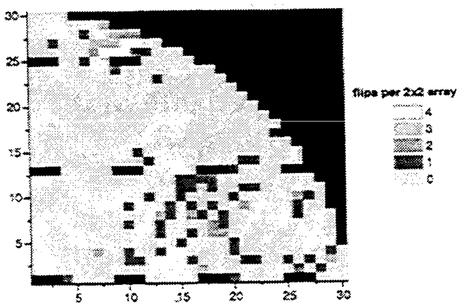
- Circularly symmetric aperture
- Polarization flip at particular I
- Possible factors:
  - I & E distribution
  - Strain
  - Birefringence
  - Dichroism





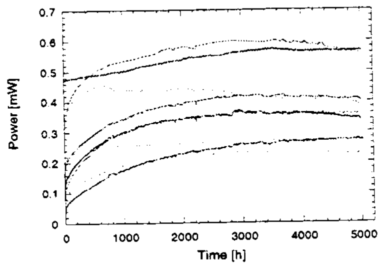
Polarization flips: distribution

- Measurement
  - PI curve w/ pol filter
- Current range
  - $0 < I < 1.5 \cdot I_{th}$
- Polarization stability
  - Typical ~ 4% flips
  - Smaller apertures are better



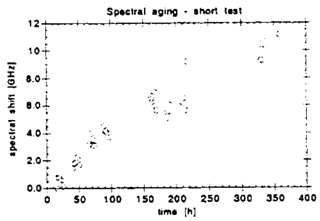
Lifetime & aging

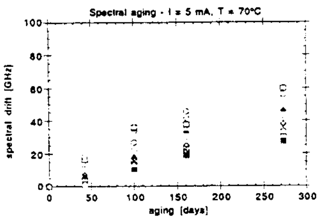
- Continuous operation
  - 60 lasers
  - $25 \leq T \leq 100°C$
  - Power monitored
- Demonstrated
  - ~ 10'000 h
- Planned expansion
  - > 2'300 lasers
  - $T \leq 150°C$



Spectral aging

- Lock to 780 nm Rb line
  - Resolution ~ 0.2 GHz
- Short term red shift
  - 0.1 - 1.0 GHz / day
- Long term red shift
  - 0.15 GHz / day
  - $3 \cdot 10^{-4}$ nm / day
- Current adjustment
  - 300 μA / year





Summary

- VCSELs are great
  - Low power & high efficiency
  - Wavelength & linewidth
  - Manufacturability
- VCSELs need work
  - Lifetime & aging
  - Polarization stability