Stable Narrow-Line VECSEL Operation for Sodium Guide Star Generation

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Why new Na LGS technology?

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- The bigger our telescopes get, the greater is the need for sodium guide star lasers with reduced cost per watt (CPW) – because we need more of them
- A potentially stronger driver: the lower the CPW, the more cost effective it becomes to put Na LGS on *smaller* telescopes where the laser represents a larger fraction of the overall facility cost
- $CPW_{2019} \sim 5 \times 10^4$ USD/W
- How low can we go?

Laser requirements

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- The laser needs to operate at 589.0 nm … of course

- Excellent frequency stability against changes in ambient temperature, gravity vector, pressure

- In addition to lowest cost, low size, weight, and power (SWAP) would be valuable as well

The VECSEL approach

- A vertical external-cavity surface-emitting laser (VECSEL) is a good candidate
  - Solid state gain medium
  - Tailored wavelength
  - Compact form
- Power can be scaled up by adding more VECSEL devices into the cavity
- Our approach is to make a multi-VECSEL laser at 1178 nm with external second harmonic generation to 589 nm
  - Goal: 20 W of yellow light, single frequency, within a compact footprint, while reducing CPW by 3x

A single-VECSEL laser

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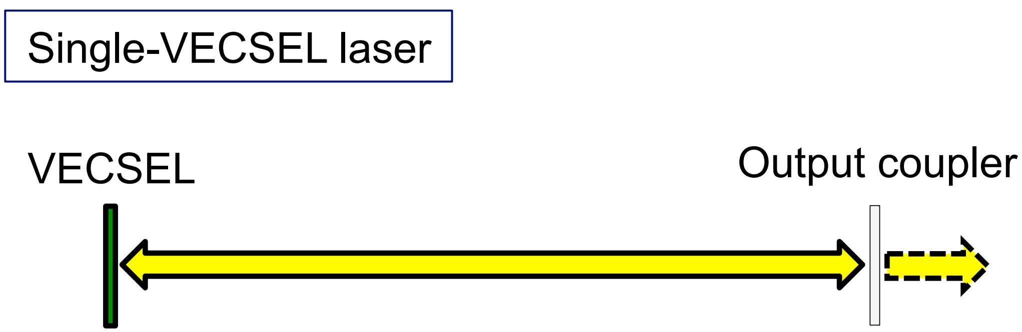
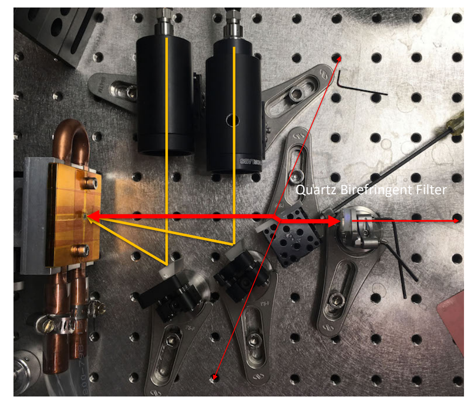
- A VECSEL is a semiconductor material that is not transparent: it must therefore form one of the mirrors in the cavity





A two-VECSEL laser

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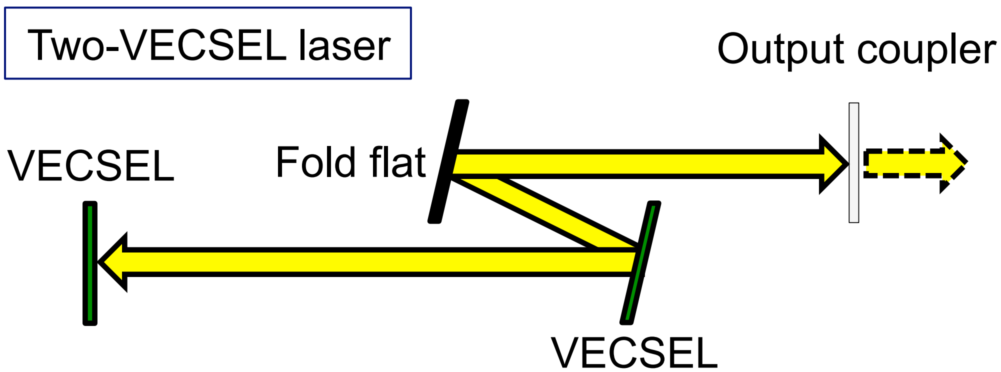
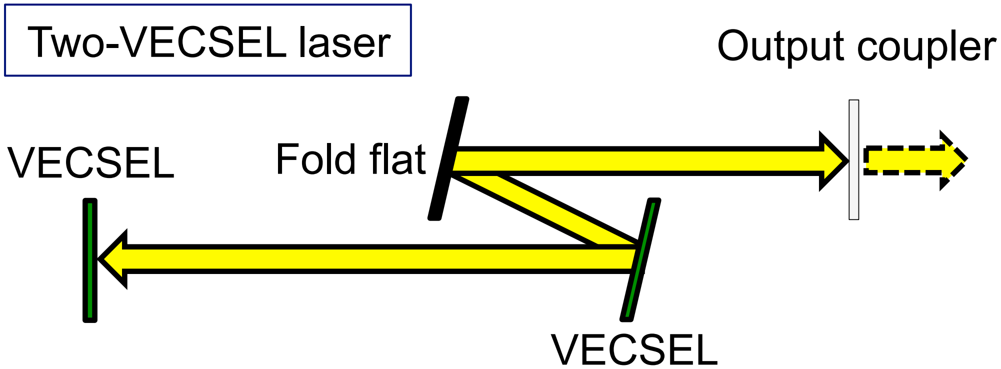
- A VECSEL is a semiconductor material that is not transparent: it must therefore form one of the mirrors in the cavity



A two-VECSEL laser

- A VECSEL is a semiconductor material that is not transparent: it must therefore form one of the mirrors in the cavity

Two-VECSEL laser



But this means putting a VECSEL at a fold in the cavity because there's only one end (that doesn't have an OC)

Gain media at a fold

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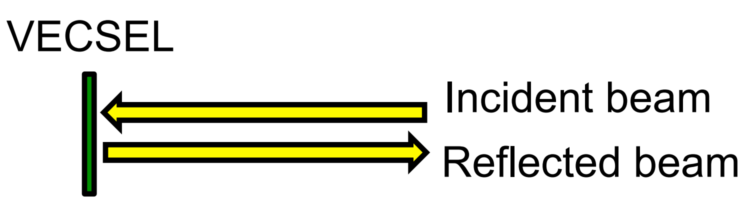
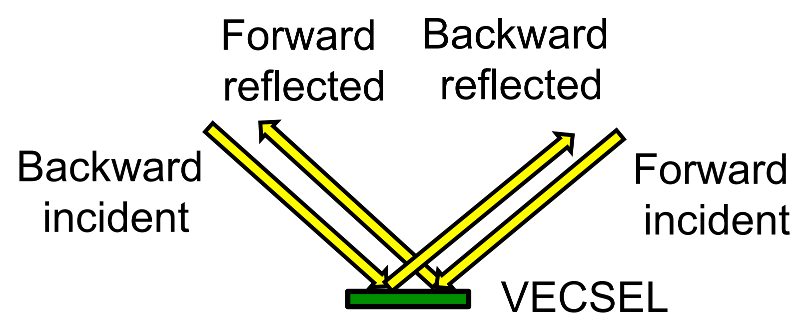
- In a resonant cavity, there’s a qualitative difference between putting a gain mirror (e.g. a VECSEL) at a fold rather than at the end of the cavity.

Cavity end



Interference between TWO beams

Cavity fold



Interference between FOUR beams

Gain media at a fold

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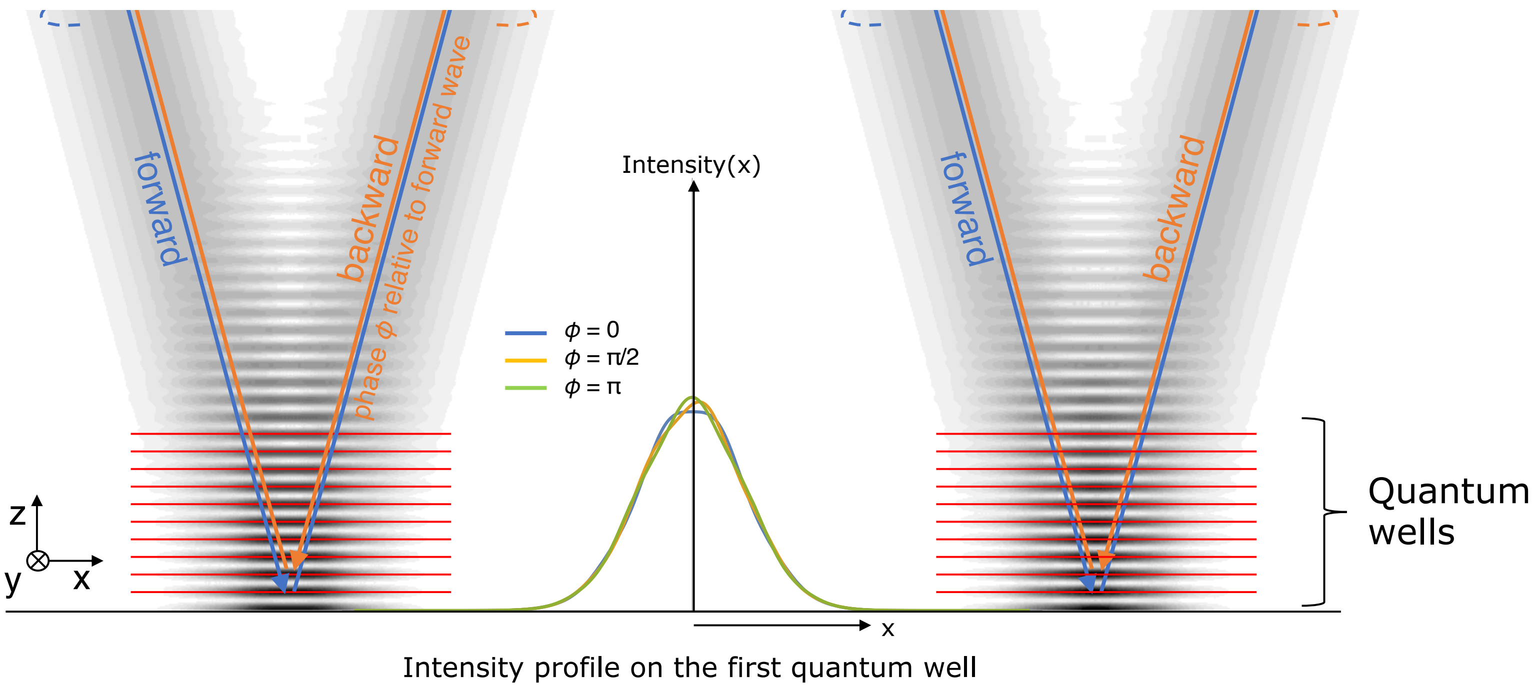
- Two-beam interference results in a stable standing wave with wavelength determined by the quantum well spacing.
  - There's just a single solution with the quantum wells of the VECSEL at the antinodes of the wave which the laser will settle to
- Four-beam interference introduces enough degrees of freedom that there are *many* solutions
- Result: laser will mode hop all over the place and be very difficult to stabilize

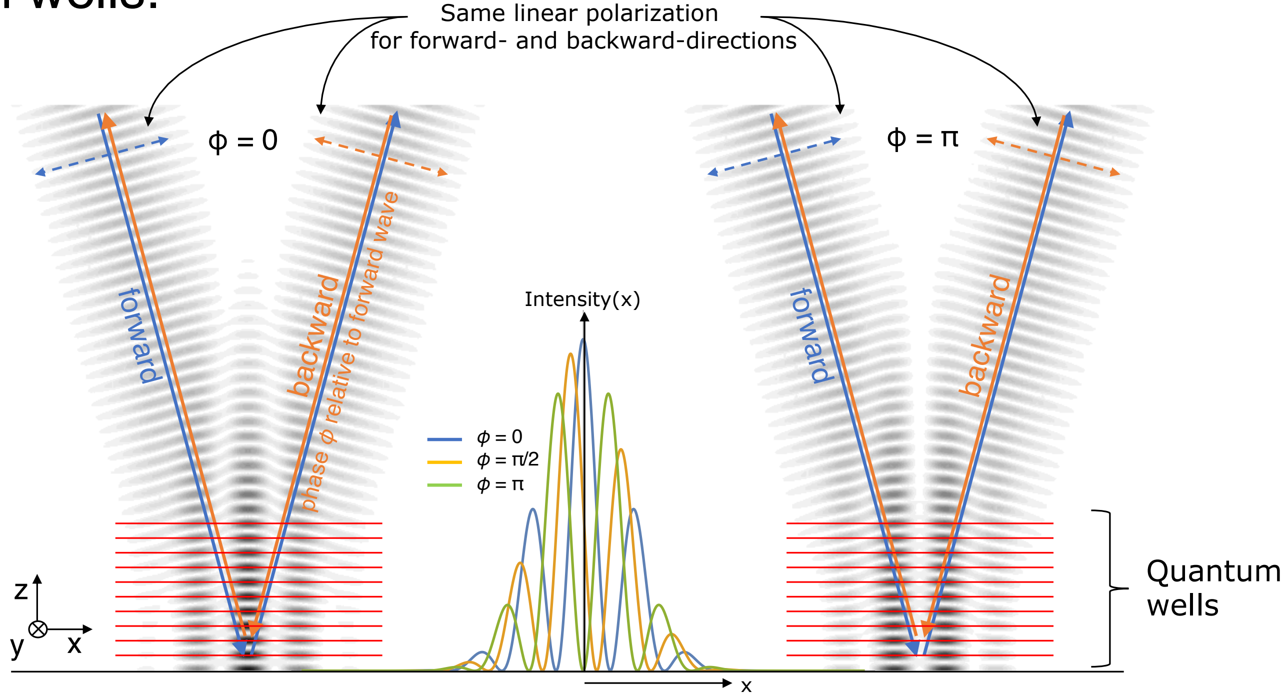
“Good” standing wave

- In the two-beam configuration, a clean standing wave is established at the quantum wells, which introduce “resonant periodic gain”



Uncontrolled modes

- In the four-beam configuration, many phase relationships between the beams (i.e. modes of the cavity) all result in antinodes at the quantum wells.



Intensity profile on the first quantum well

Stabilizing the multi-VECSEL laser

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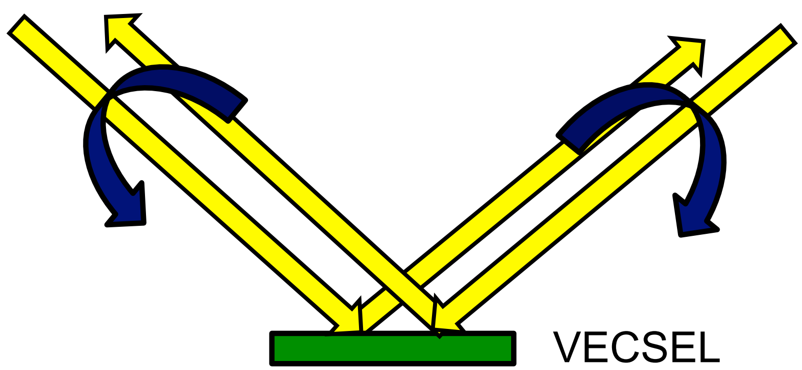
- The fundamental problem to power scaling a VECSEL laser by adding more devices in the cavity is the coherence between the forward and backward beams.
- So – can we find a way to suppress that coherence?
- Yes – by imposing opposite circular polarizations on the two beams, creating a “twisted mode” cavity



Twisted mode standing wave

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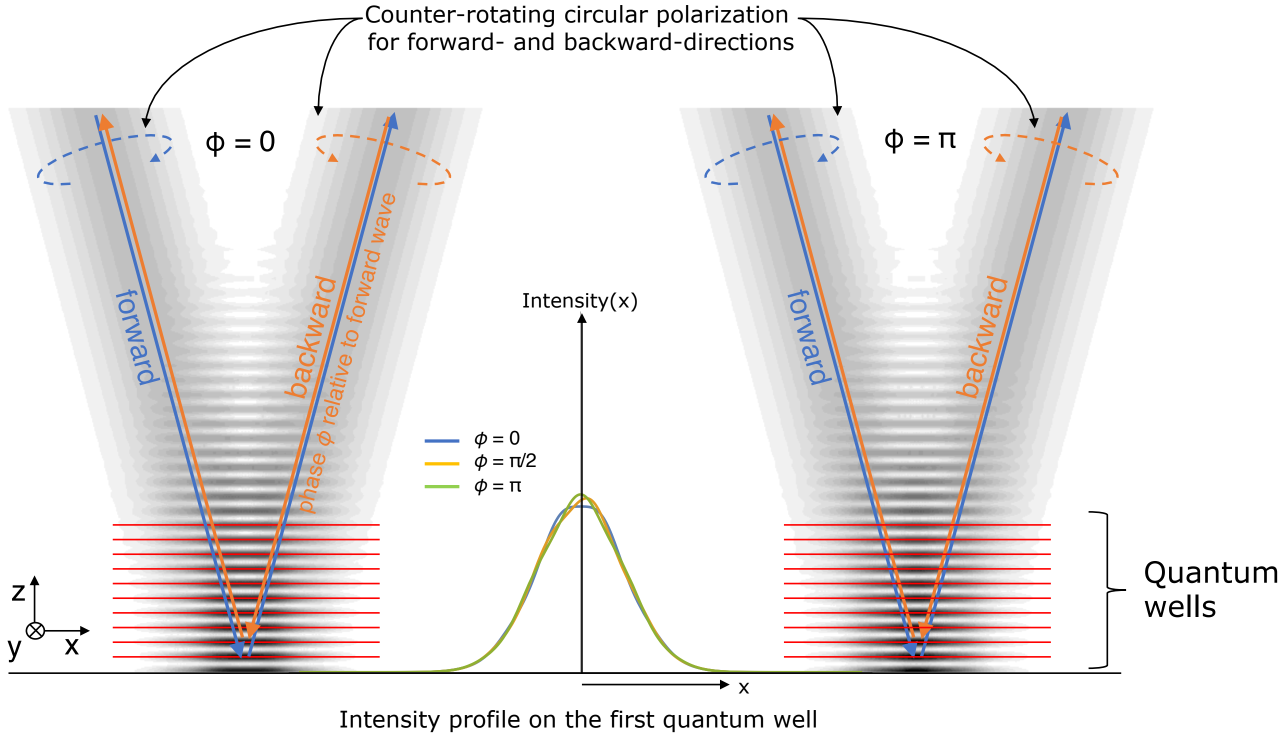
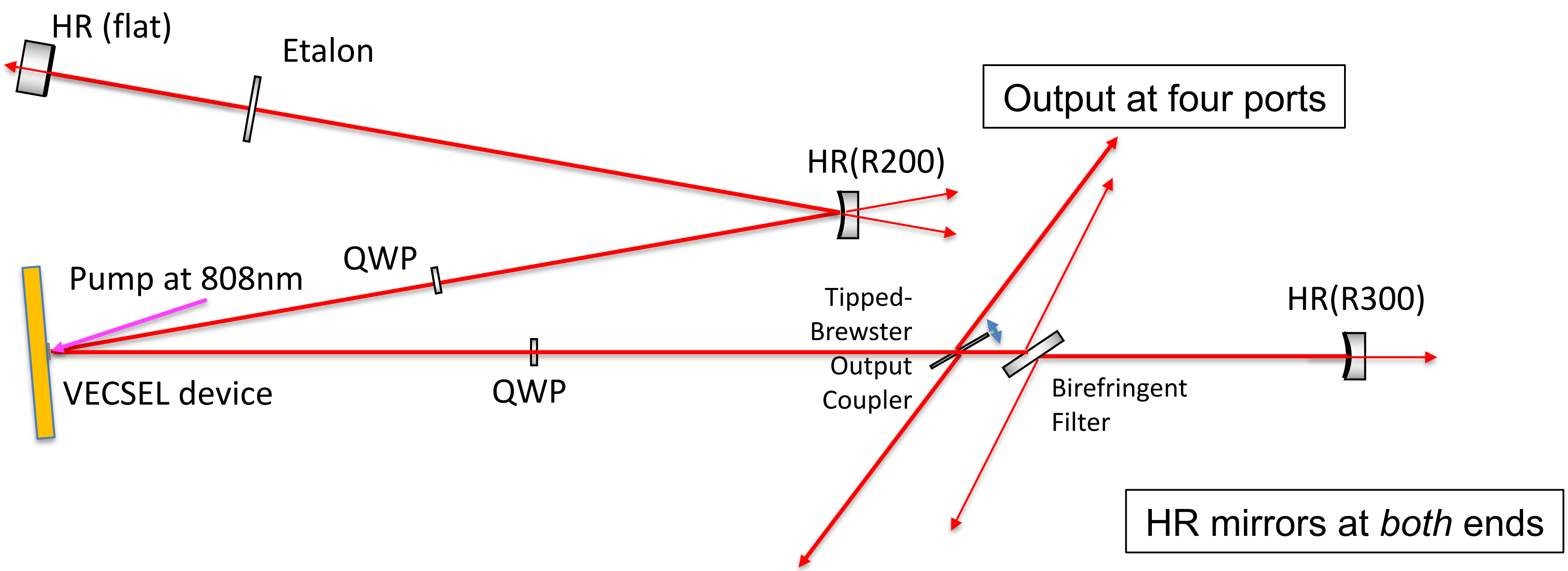
- Now the forward and backward beams are *independently* constrained to form standing waves as if the VECSEL were at the end of the cavity



Experimental arrangement

- First experiment: single VECSEL at a fold
  - Quarter-wave plates introduce opposite circular polarizations into two beams
  - Variable output coupling using an adjustable Brewster window



Single-VECSEL layout

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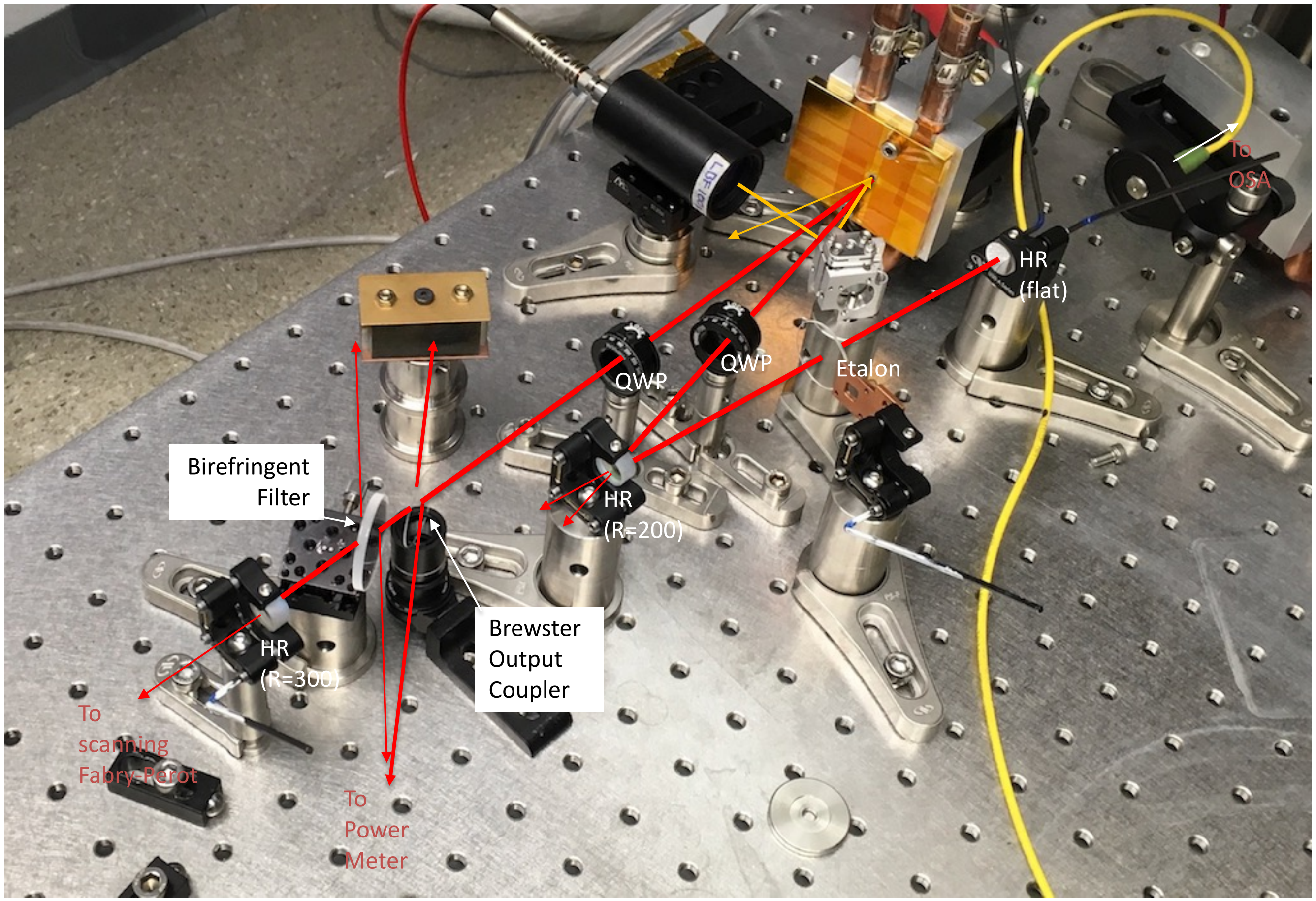
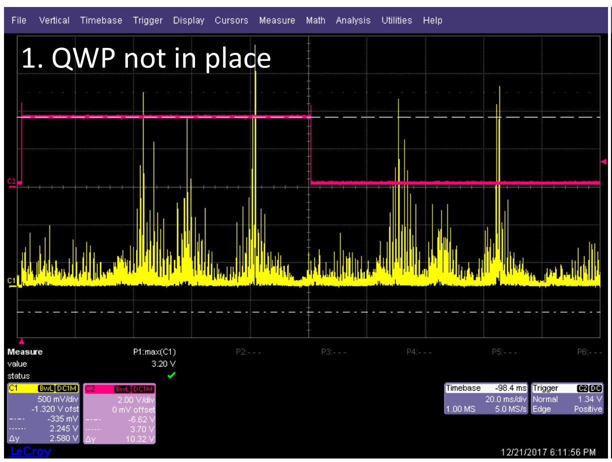


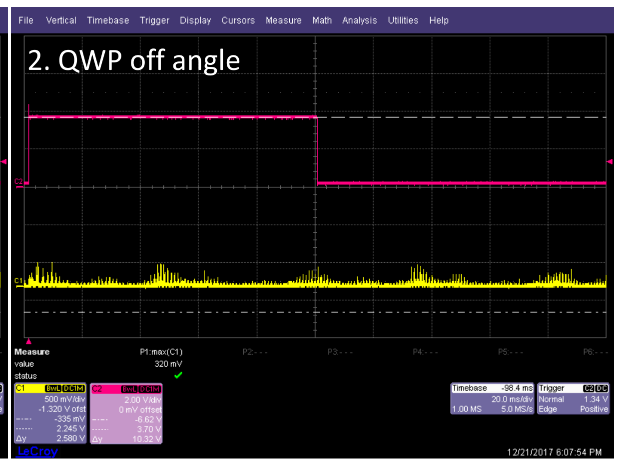
Single-frequency results

Spectra measured with a Fabry-Perot interferometer in three conditions:

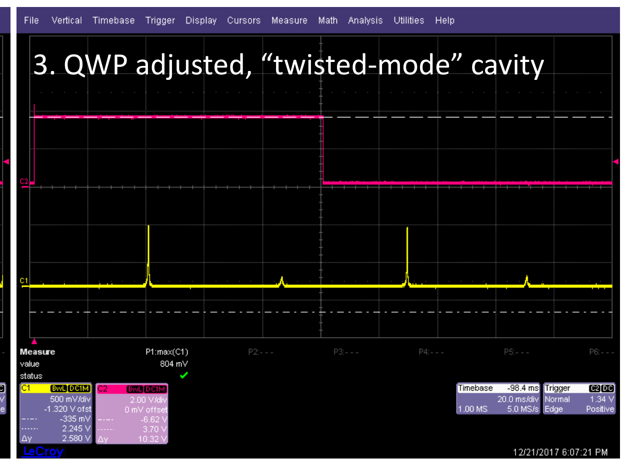
1. QWP removed from cavity
2. QWP installed, but deliberately set at wrong angle
3. QWP installed and correctly oriented



A hideous mess



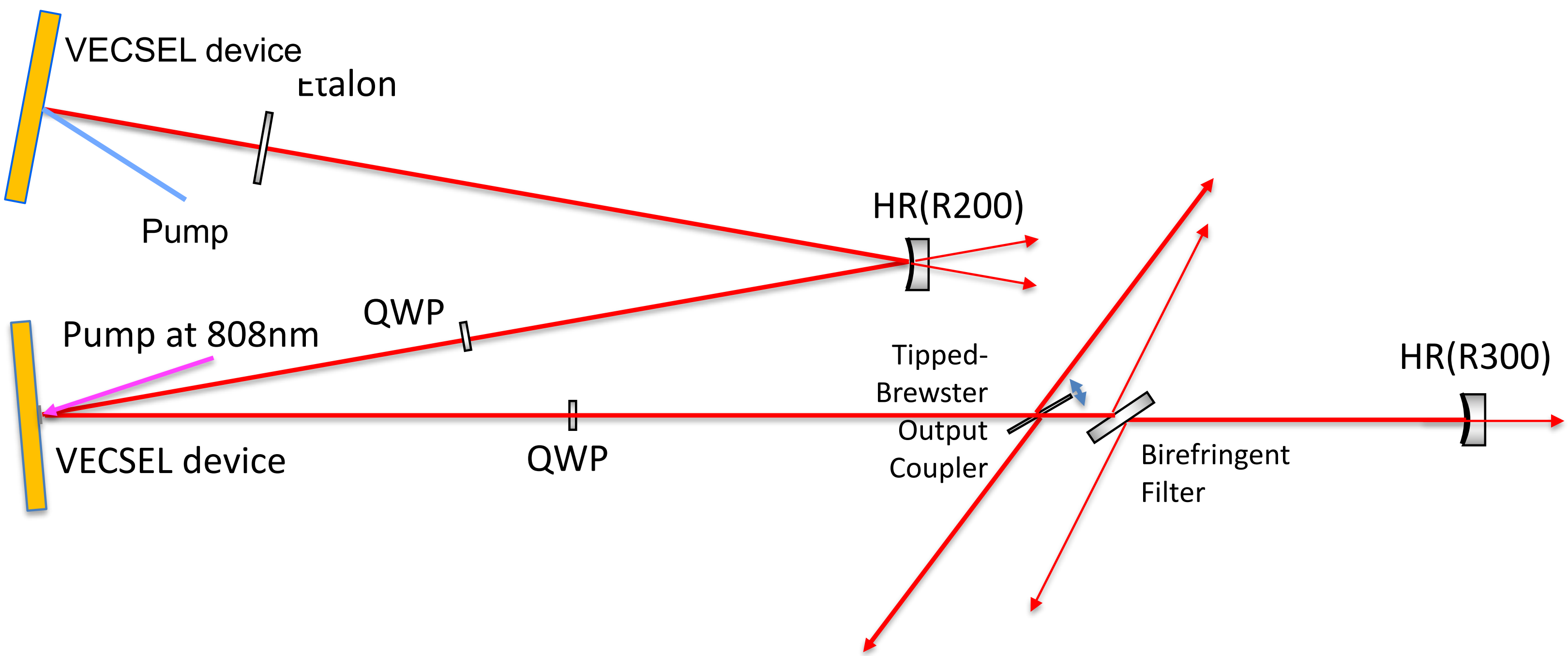
Still a mess, and low power



Single frequency!

Two-VECSEL experiment

- Second experiment: one VECSEL at a fold, another at the end of the cavity



Two-VECSEL results

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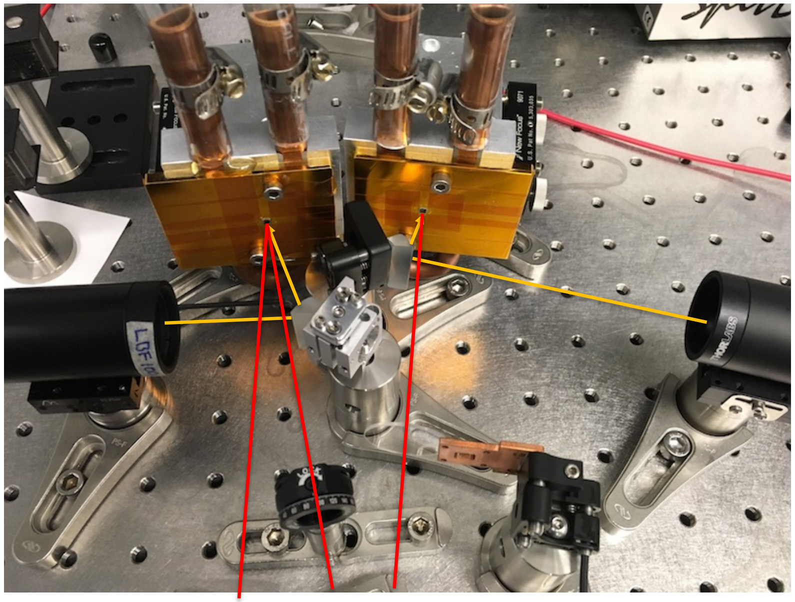
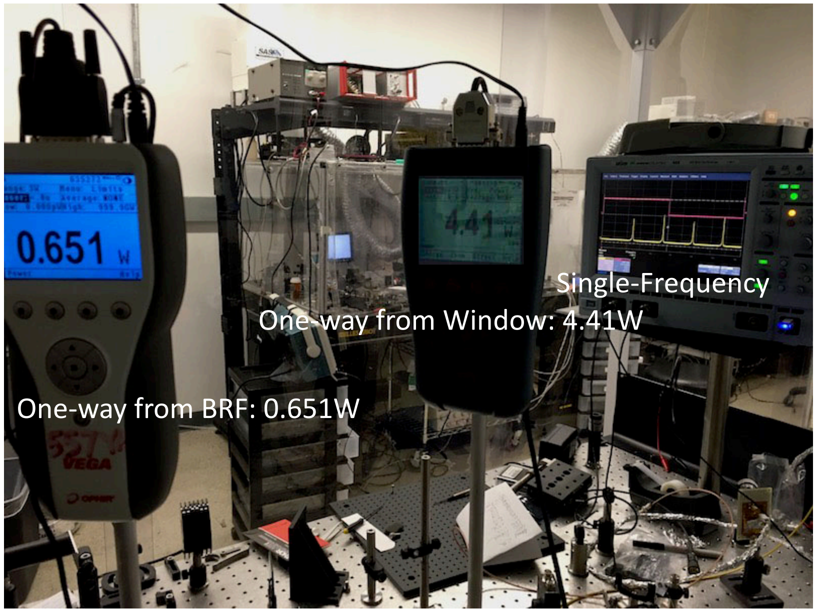
Setup in the lab



Output power measurement



- Total output power = 2x0.651 + 2x4.41 = 10.12 W single frequency

Summary and next steps

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- Total power output with 2 VECSELs exceeded 10 W single frequency at 1178 nm
- No special precautions taken in laboratory environment (e.g. thermal control, air flow, vibration)
- Stable single-frequency operation observed for periods > 15 minutes
- Demonstrated twisted-mode stable single-frequency operation
- Next steps:
  - Expand cavity to include four VECSEL devices (2 more on their way from Finland now)
  - Install conventional output coupler with 6% transmission
  - Add frequency-doubling external cavity to 589 nm based on PPsLT crystal