Real-world Yb:fiber laser frequency comb
Outlines

- Motivations
- Difficulties and solutions
- Cavity configurations
  - 500 MHz and 750 MHz
  - 1GHz proposed
- Tapered crystal fiber for spectrum broadening
- Results and discussions
- Summary
Motivations

- **Ti:sapphire laser comb**
  - Directly generate fceo by PCF, without amplifiers
  - Up to 1 GHz repetition rate (10GHz)
  - Long term stability?

- **Fiber laser combs**
  - Not yet comparable to Ti:sapphire laser combs in
    - Mode spacing (250MHz vs 1GHz)
    - Wavelength (near IR vs visible)
    - Simplicity (amplification + pulse compression vs direct TL pulse)
f₀, or fceo: f-to-2f technique
Octave-spanning spectrum is required!
Introduction

Trend
- low phase noise
- high repetition rate
- high power
- wide spectral coverage
- great robustness

Methods
- Solid state based
  - High repetition rate capability
  - Low noise
  - Lack long term stability
  - High cost
- Fiber based
  - Long term stability
  - High noise
  - Lack high repetition rate capability
  - Low cost

2300 Small Exoplanets

Up next: Habitable Zone Earths
Kepler-11
The Density of Kepler-10b

Planet Transit

Doppler of Star:
Mass of Planet

Size = 1.4 \( R_{\text{Earth}} \)

Time (hours)
Keck Observatory
Doppler Follow-up of Kepler’s Earth-Like Planets

Keck Telescope
Mauna Kea, hawaii
Period = 0.84 days

Period = 45.29 days

Kepler-10 Light Curve
1/1000 pixel are revealed as small changes in the light in neighboring pixels. Final Doppler Precision: 1 meter / sec

But the spectrograph is not calibrated. It needs a precise calibrator---frequency comb!
Motivations

- **Our research goal**
  - 500MHz~1GHz fiber laser as the source for
  - 40GHz astro-comb

- **Other applications**
  - Optical frequency measurement
  - Optical to Radio frequency conversion
  - Optical ranging
Motivations

- Why large mode space necessary:
  - Astro-comb: Resolution of China Astronomical Observatory
    R=60,000 → >32 GHz astro-comb @ 500nm
  - for side-band suppression because
    \[ \Delta \nu_{LW} \propto \Delta \nu_{FSR} \]
  - To avoid mode number uncertainty
- How to achieve high rep rate laser and comb
  - Shortest fiber and
  - Minimized free-space
  - Low energy spectrum broadening
- Difficulties
  - Principle: low pulse energy → low nonlinear phase shift
  - Practice: components (fiber, WDM, grating, etc.)
  - High nonlinear photonic crystal fiber: commercial one still needs nJ pulse energy
Problem with FP filter: side modes

Repetition rate: 250MHz

Repetition rate: 500MHz
Cavity selection

- Ring or linear, NPE or SESAM
- Ring cavity with NPE:
  - Limited to \(~\text{N}00\) MHz
  - NPE=fast (fs) saturable absorber
  - Broader spectrum and shorter pulses
- Linear cavity with SESAM:
  - \(>1\text{GHz}\) possible (3GHz, MIT)
  - SESAM=slow (ps) saturable absorber
  - Narrower spectrum and broader pulses
- We stay with \textbf{Yb:fiber ring cavity, but try to make it work at the highest rep rate}
Solutions

- **Principle**
  - Short fiber: less dispersion $\rightarrow$ shorter intracavity pulses $\rightarrow$ nonlinearity remains
Recall the history of femtosecond Ti:sapphire lasers: intuitive “length law”: pulse width vs. crystal length.

Of course it is also the matter high order dispersion.
Simulation: pulse width over fiber length (pulse repetition rate for **ring cavity only**)

"Length-law" does work for fiber lasers

- **soliton**
- **self-similar**
- **stretched pulse**

Shorter fibers
Solutions

- **Practical devices**
  - **Fiber:**
    - SM fiber, as short as possible
    - gain fiber: high doping 1200dB/m, 1600dB/m
  - **WDM:**
    - semi-WDM

- **Grating pair: round trip to single trip**
  - very short grating space (~1-2mm)
  - lateral chirp negligible
  - lower third order too
Benefits from short fiber cavity

- More like a solid state laser, but relaxed pointing instability!
- **Direct TL short pulse output**
  - Sub-50-fs pulse without need compression
  - Direct octave spanning spectrum via PCF
  - Low noise, high contrast fCEO
- **Ultra-stable**
  - Less sensitive to environment perturbation, because of the short fiber
Ring cavity for 500MHz

- YDF
- PBS FR
- PBS
- λ/4
- λ/2
- Collimator
- "980nm LD"
- Output
- WDM
- Mirror/PZT
- Grating Pair
- Collimator
Ring cavity for 500MHz

Diagram with components labeled:
- YDF
- Collimator
- PBS
- FR
- λ/4
- λ/2
- 980nm LD
- Mirror/PZT
- Grating Pair
- Output
- Mirror
Ring cavity for 750MHz
Route for 1GHz fiber laser

- Any other device can be shortened?
  - Faraday rotator 5cm: not able to shorten without new materials developed.
  - But, do we really need very good isolation?
    - Only a few percent loss is enough for uni-directional
    - For example, 22.5 degree makes 50% returning loss.
    - 22 degree Faraday rotator is on the way

- Waveplate holders:
  - New holder: two waveplates mounted on both side of the holder with independent rotation
Re-configuration of cavity for 1GHz
Results for 528 MHz fiber laser

Guizhong Wang, Tongxiao Jiang, Chen Li, Hongyu Yang, Aimin Wang, and Zhigang Zhang, Opt. Express, 2013

Direct output sub-50fs pulses by fine adjust on grating separation

44fs
The direct output pulse is 68 fs

By varying the intra-cavity grating pair, we can have the shortest pulse without extra-cavity dispersion compensation

<table>
<thead>
<tr>
<th></th>
<th>Intra-cavity Grating separation</th>
<th>Extra-cavity Glass length</th>
<th>Output pulse width</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>2.8 mm</td>
<td>57 mm</td>
<td>68 fs</td>
</tr>
<tr>
<td>B</td>
<td>2.1 mm</td>
<td>24 mm</td>
<td>44 fs</td>
</tr>
<tr>
<td>C</td>
<td>1.7 mm</td>
<td>0 mm</td>
<td>46 fs</td>
</tr>
</tbody>
</table>

Tapered crystal fiber for spectrum broadening

- A comb needs octave-spanning spectrum for f-to-2f beating for fceo
- General photonic crystal fiber needs relatively higher pulse energy >1nJ
- High repetition rate fiber laser delivers less pulse energy
- Low pulse energy, or high nonlinearity becomes necessary
- Solution: taper the fiber
Tapering the fiber

Up to 120 mm

Down to 50 nm

PCF or conventional fibre

oxygen-butane Burner
Tapered fiber

Tapered silica PCF
5 µm core → 2 µm core
Tapered photonic crystal fiber: simulation

Simulation results with different d/L ratio and corresponding octave-spectrum
Super continuum generation in tapered fiber

The super continuum with different chirped pulses pumping energy
528 MHz fiber laser frequency comb

Guizhong Wang, Tongxiao Jiang, Chen Li, Hongyu Yang, Aimin Wang, and Zhigang Zhang, CLEO 2013

>30dB fceo in collinear

40dB fceo

Guizhong Wang, Tongxiao Jiang, Chen Li, Hongyu Yang, Aimin Wang, and Zhigang Zhang, CLEO 2013
Stability of the fiber comb (250MHz)

RMS: 1.5mHz

RMS: 2.5mHz
Integrated into one box

- compressor
- amplifier
- fceo detection
- oscillator

Performance is under examination

600×900mm

290×590mm
1GHz fiber laser (in progress)
Summary

- We have developed high repetition rate fiber ring lasers up to 750MHz and high nonlinear tapered PCF

- Those fiber lasers
  - Deliver sub-50 fs near TL pulses
  - Help to directly generate octave-spanning spectrum from 100MHz to 500MHz
  - Help to achieve high contrast fceo

- Comb performance is under improving

- Can they be a real-world comb?
Future work

- Large frequency space combs:
  - 750 MHz fiber comb
  - 1 GHz fiber comb
  - 40 GHz astro-combs for astro-comb

- Direct generation of octave spanning spectrum for combs
Thank you for your attention