Towards direct generation of wide coherent microcombs with photonic belt resonators

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Optical frequency comb

\[ f_n = f_0 + nf_{rep} \]

- octave span for F-2F locking of \( f_0 \)
- mode locking for direct measurement of \( f_{rep} \)
- \( f_{rep} \) low enough to directly measure
- Overall stability comes from external atomic clock

Image from: http://www.menlosystems.com
Micro-comb challenges

Can we get most of the comb features from a single microresonator?

- Measurable $f_{rep}$
- Octave span and power sufficient for F-2F (or 2F-3F)
- Mode locked operation (solitons)

A good example of state of the art: soliton state with 2/3-octave span

There are many different platforms


Images from k-lab.epfl.ch and http://www.menlosystems.com
Crystalline WGM resonators

Record optical (up to $Q > 10^{11}$) and compact mode volume lead to efficient comb generation

Frequency comb observed in a resonator with engineered spectrum. The TE$_{1101,1101,1}$ mode near 1560.3 nm (loaded $Q = 8.4 \times 10^7$, intrinsic $Q = 2 \times 10^8$) was pumped. Resonator diameter is 403 μm. Strong geometric dispersion leads to overall normal resonators dispersion. Over a hundred comb lines spanning more than 200 nm (23.5 THz), limited by OSA range, are observed with only 50 mW of optical pump power.

Table 1. Parameters of Various MgF$_2$ Microresonator-based Frequency Combs

<table>
<thead>
<tr>
<th>Reference</th>
<th>FSR, GHz (diameter, μm)</th>
<th>Optical Q factor near $\lambda = 1.55$ μm</th>
<th>Pump, mW</th>
<th>Pump $\lambda$, μm</th>
<th>Comb span, nm</th>
</tr>
</thead>
<tbody>
<tr>
<td>[9]</td>
<td>107 (700)</td>
<td>$&gt;10^9$</td>
<td>600</td>
<td>2.45</td>
<td>~200</td>
</tr>
<tr>
<td>[8]</td>
<td>68 (1000)</td>
<td>$\sim 2 \times 10^8$</td>
<td>500</td>
<td>1.56</td>
<td>~300</td>
</tr>
<tr>
<td>This work</td>
<td>172.44 (403)</td>
<td>$\sim 2 \times 10^8$</td>
<td>50</td>
<td>1.56</td>
<td>&gt;200</td>
</tr>
</tbody>
</table>


Need dispersion engineering to reach octave span
Dispersion engineering in PBR

Enables dispersion engineering in crystalline WGM resonators
Photonic belt resonators

(a) Whispering gallery resonator
- Axially symmetric substrate, high optical Q factor
- Substrate
- Microstructured resonator
- Resonator on a chip
- Waveguide
- Substrate
- Ridge waveguide, dispersion and spectrum control

(b) Substrate: MgF₂, R=0.75mm
- Waveguides: 7x5 micrometers

Image of the resonator with a close-up view showing the details of the substrate and waveguides.
Single mode PBR in one octave

1 > \frac{wn}{\lambda} \sqrt{\frac{2h}{R - h}} > 0.5

Unexplored potential of PBR

Dispersion of MgF₂ PBRs, R=1320 mkm, single mode

- Sphere
- PBR w=9 h=7
- Truncated PBR w=9 h=7

Wavelength, μm

Dispersion, ps/(nm·km)
More dispersion engineering: CaF$_2$
More dispersion engineering: CaF$_2$
Dispersion engineering in MgF$_2$ PBR

Microstructured waveguides and corresponding dispersion.

a, Each of the 8 images represents an area sized 25x45 micrometers. The optical images of the waveguide cross sections are shown along with the mode intensity maps obtained with FEM modelling.

b, Numerically computed total cavity dispersion for the waveguides shown in a). The waveguide “S” with Gaussian waveguide shape, similar to previously reported single mode resonators, has the same dispersion as an ideal sphere.

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Frequency combs generated in photonic belt resonators with 300 mW of pump at $\lambda=1560$ nm (192.4 THz). 

**a,** The primary comb in waveguide ``C'' starts at N=408 in contrast to N~30 in waveguides ``A'' and ``B''.  

**b,** Secondary comb formation in waveguide ``C'' starts as the laser detuning is reduced.  

**c,** Comb states at a minimum stable detuning. The comb from the waveguide ``C'' contains nearly 2000 lines spanning 100 THz. Inset shows cavity FSR--spaced comb lines. The comb from the waveguide ``S'' shows evidence of avoided mode crossing.

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First octave spanning comb with repetition rate below 50 GHz and pump power of less than 1 W

Octave spanning frequency comb and its beatnote. Waveguide “C” produced comb lines spanning across over one octave (blue). The noise level for large laser detuning where no comb is generated is also shown (black). The gap could be explained by near-IR fiber absorption or by particular resonator dispersion and spectrum. Resonator intrinsic $Q=50 \text{ million}$, pump power $600 \text{ mW}$, FSR $46 \text{ GHz}$.

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“Frequency jump*” excitation of solitons


MgF$_2$ PBR

- Surface scattering limited (intrinsic) $Q=10^9$ @ 1561 nm.
- Single TE mode operation (TM is suppressed)
- Dispersion engineering

Image obtained by Risaku Toda, optical profilometer MDL JPL.
Solitons in MgF$_2$ PBR, 25.8 GHz

Characteristic soliton steps in transmission

Pump is gone
PBR features and prospects

- Probably the most efficient dispersion engineered microcomb
- Fluoride crystals and other materials
- $Q>10^9$, compact optical mode volume = efficient comb generation
- UV, visible, near-IR and mid-IR operation
- Soliton states demonstrated
- Dispersion engineering for octave comb span
- Single mode operation

Next step: broadband solitons

- Heterogeneous integration, or
- Fluoride chip based comb generators
PBR challenges

Fabrication
Significant dispersion change is achieved by \textit{50 nm} geometry modification.
Current fabrication precision \textit{\sim 500 nm}.

Imaging
SEM – leads to surface charging effects, requires coating, slow.
Profilometer – not capable of side wall imaging, slow.
Imprint lithographic method – new technique, fast (2-3 hours)

Optical 500x    Micro-imprint