Yb-doped Mode-locked fiber laser based on NLPR

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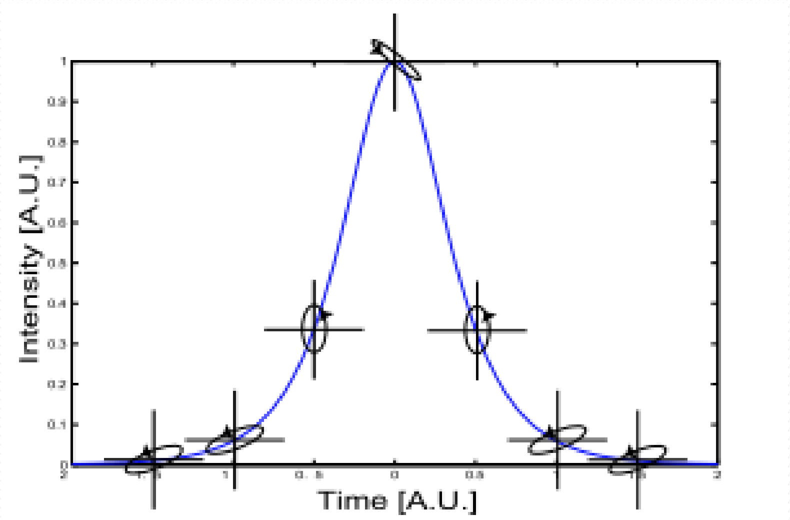
Yan YOU

Mode locking method-NLPR

- **Nonlinear polarization rotation(NLPR)：** A power-dependent polarization change is converted into a power-dependent transmission through a polarizer. NLPR converts the differential phase shift to amplitude modulation.
- stable soliton
- stretched-pulse
- self-similar
- all-normal-dispersion pulse



Soliton

- Solitons are caused by a cancellation of nonlinearity and dispersion
- work in anomalous GVD regime, sech ^{2} pulse shape
- For stable soliton fiber lasers the energy of a single pulse is limited by the nonlinear phase shift induced by the high peak power. The pulse will break into multiple pulses when the energy rises to 0.1 nJ. The pulse can tolerate only a small nonlinear phase shift $\Phi_{NL} << \pi$
- Solitons are static solutions of a nonlinear wave equation

Stretched-pulse

- Analog to dispersion-managed soliton, an alteration of positive and negative dispersion part inside a laser cavity.
- work in net GVD varies from small anomalous to small and normal
- can reach an energy level which is one order of magnitude larger than that of stable soliton , but small than 3nJ
- the pulse width is not constant and varies along each fiber segment.
- produce highly desirable Gaussian pulse shapes and pulse spectra

Stretched-pulse

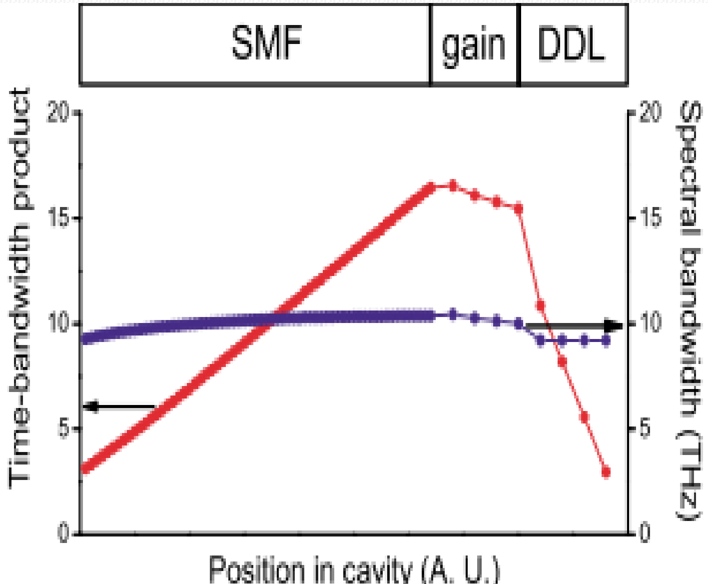
- self-starting ,not wave-breaking free
- SMF after Yb fiber the shorter the better, such that the amplified pulse propagates through the minimum length of fiber. This nonlinear effects, which impose a major limitation on the highest energy obtainable from fiber lasers.
- Nonlinearity limit pulse energy through either of two mechanisms: (i) Excess energy can result in wave breaking through the combined effects of dispersion and nonlinearity. (ii) The artificial saturable absorber (SA) can be overdriven at high peak powers, which will lead to multiple pulsing.

Self-similar pulse

- Self similar pulse/similariton, has a parabolic shape and a linear frequency chirp, wave-breaking free pulses in the propagation and convenient for efficiency compression to fs pulses.
- asymptotic solutions to the nonlinear wave equation that governs pulse propagation.
- Work in larger normal GVD compared with DM, and normal GVD tends to "linearize" the phase accumulated by the pulse, which increases the spectral bandwidth but does not destabilize the pulse. With the increasing of normal GVD, the pulse energy increases dramatically
- Pulse energy up to 10nJ has been achieved

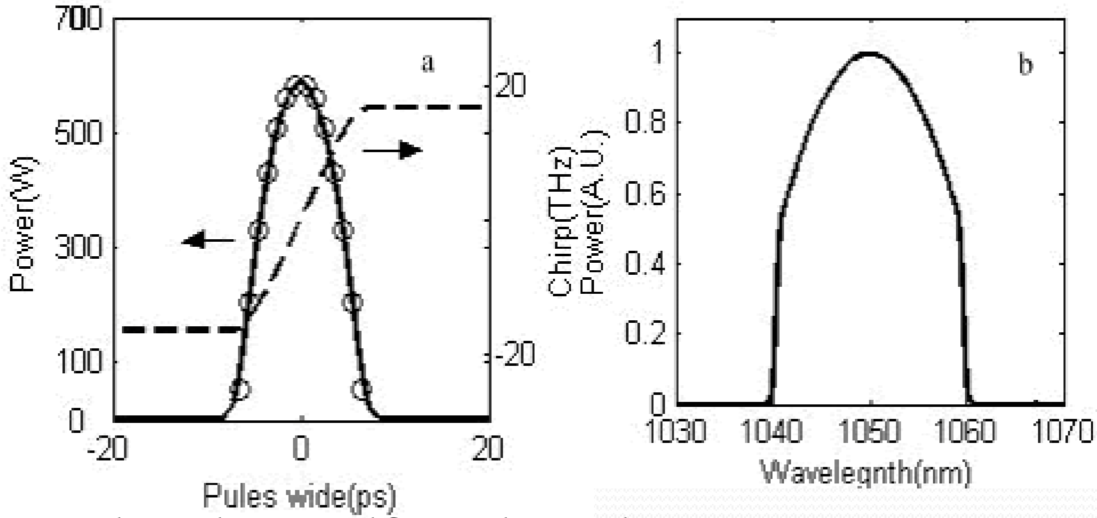
Self-similar pulse

- Evolve to fill available gain bandwidth.
- Pulse width is at a level of tens of pico-second



2004, F. O . Ilday, Self-Similar Evolution of Parabolic Pulses in a Laser

The saturable absorber is between the gain and the DDL.



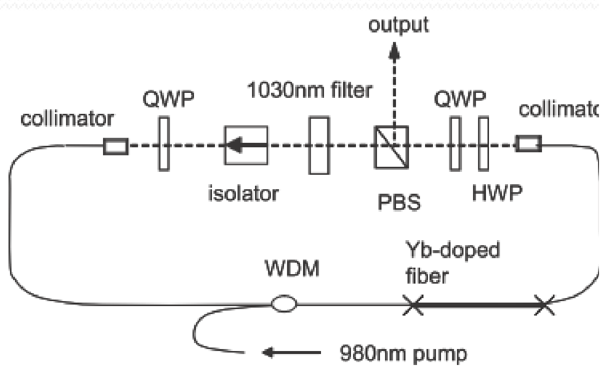
2009, Ting Lei, Numerical study on self-similar pulses in mode-locking fiber laser by coupled Ginzburg- Landau equation model

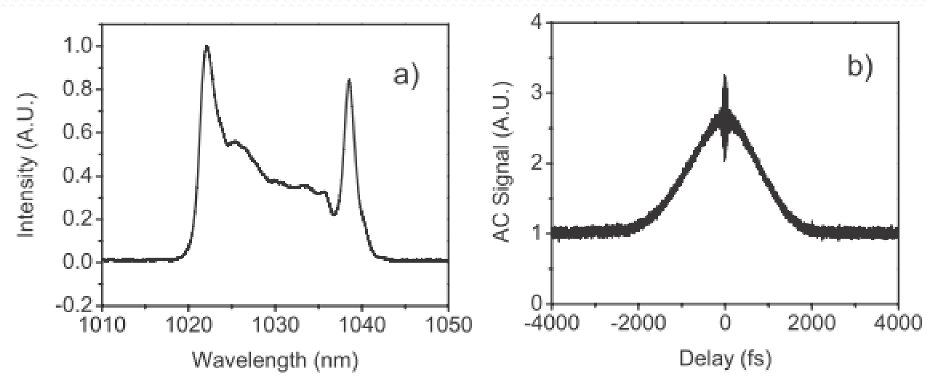
Dissipative solitons

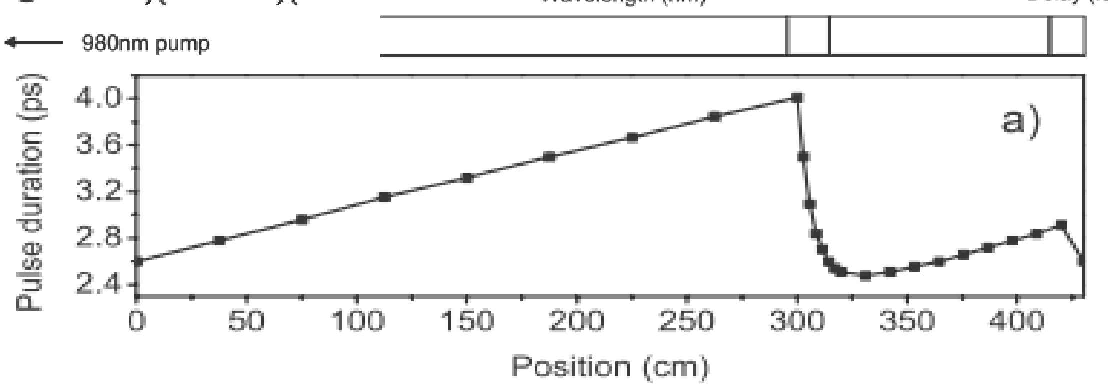
- Cavity only consists of elements with normal GVD. Normal dispersion linearizes the chirp produced by self phase modulation, generates chirped picosecond pulses, wave breaking free pulse, can be dechirped to several hundred fs.
- Mode-locking depends critically on the spectral filtering effects, provided by gain bandwidth and filter, without it, stable pulse trains are not generated.
- By rotating the spectral filter to vary the center wavelength, either of the sharp spectral features can be suppressed, which may slightly improve the pulse quality. When the spectrum changes, the magnitude of the chirp on the output pulse can change substantially, and the pulse duration.
- Pulse energy, nonlinear phase shift can be as large as 10π, pulse energy scales up to about 50 nJ.

Dissipative solitons

- The pulse duration increases monotonically in the SMF, and then decreases abruptly in the gain fiber. In the second segment of SMF the pulse duration increases slightly, before dropping again owing to the NLPR.

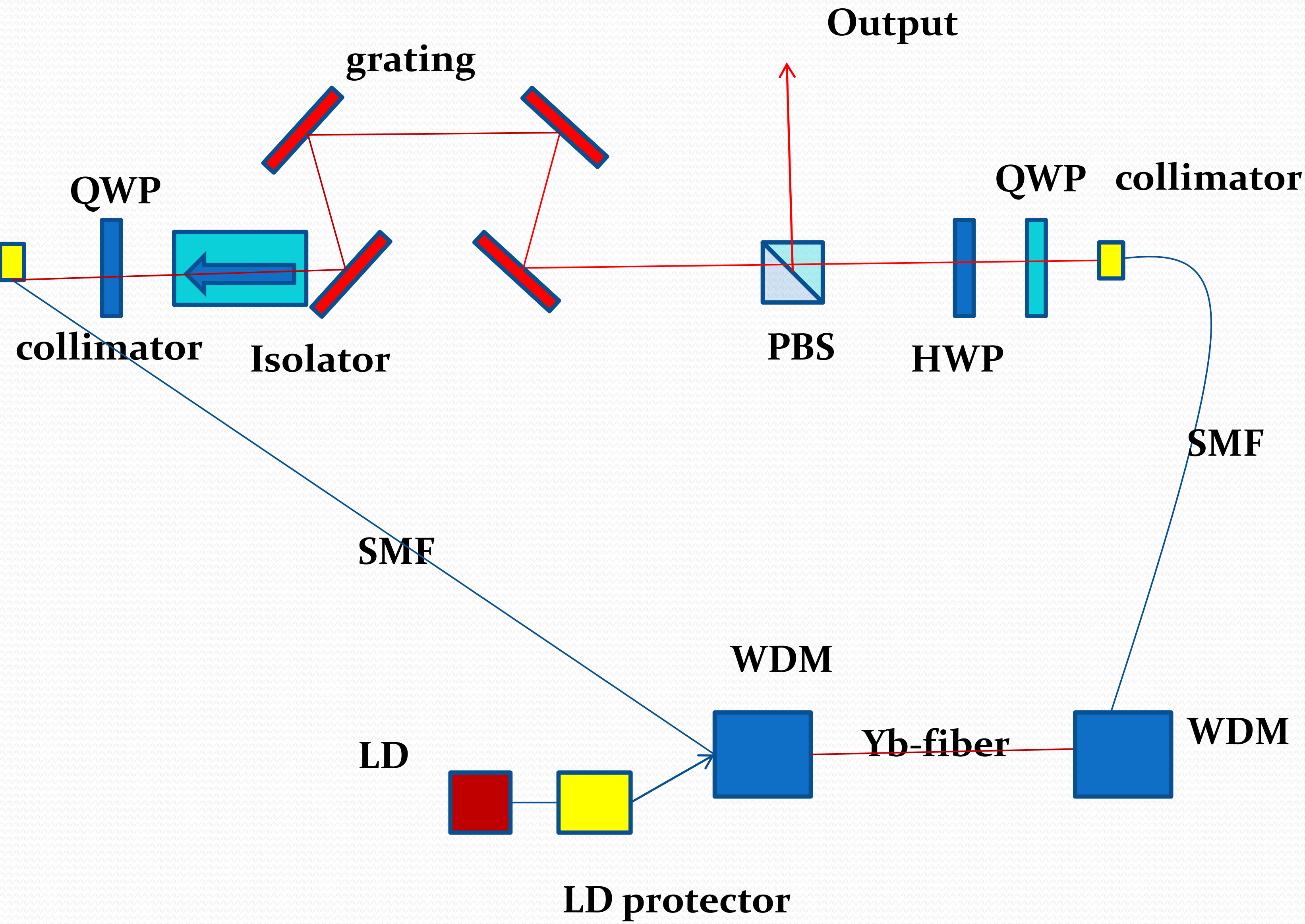






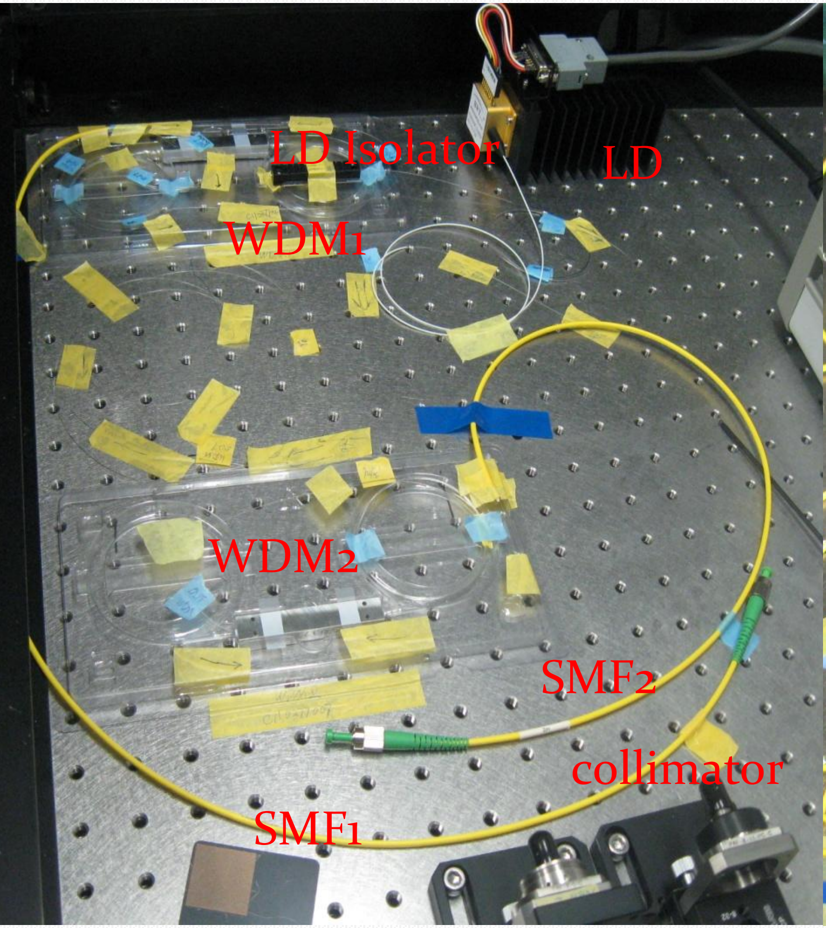
2006, Andy Chong,All-normal-dispersion femtosecond fiber laser

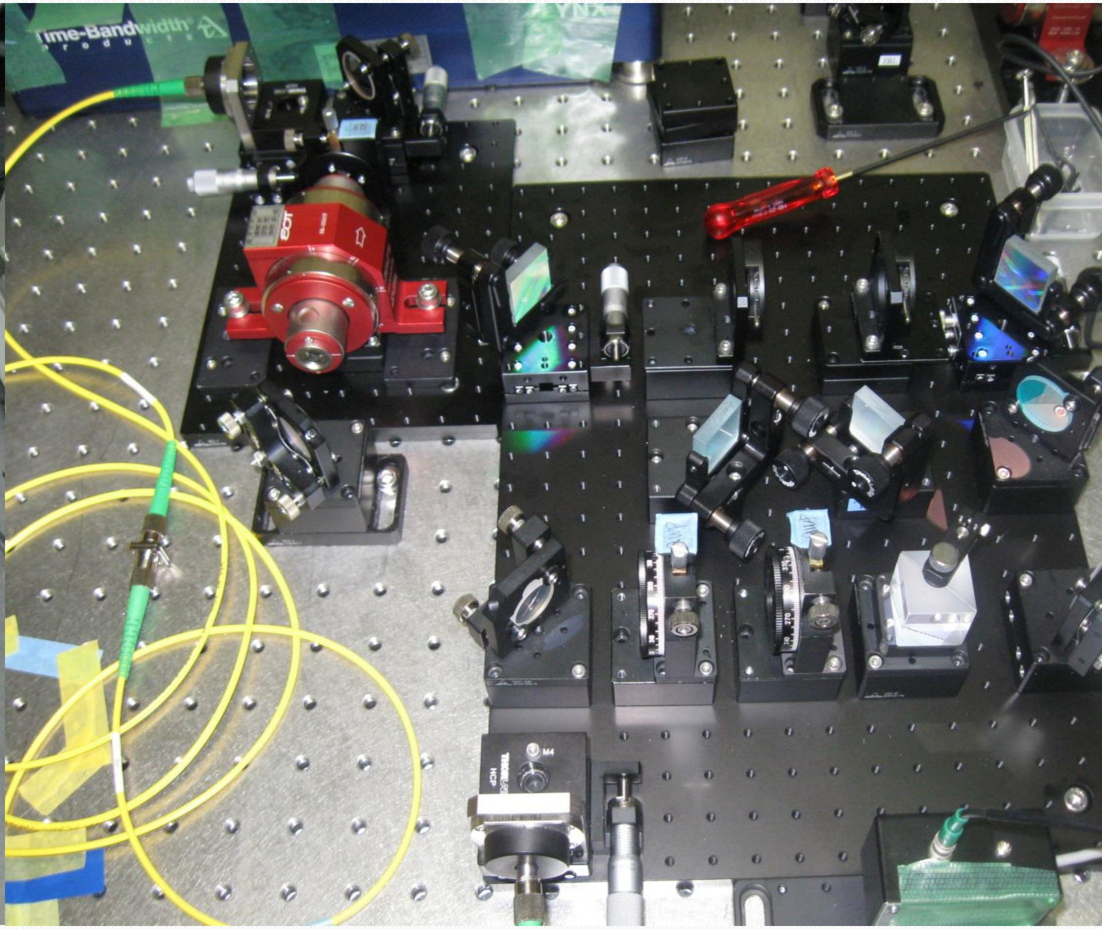
My experiments-Setup



Setup

- LD+LD Isolator+WDM1+Yb-doped fiber +WDM2+
- SMF2+free space+SMF1





Parameters of setup

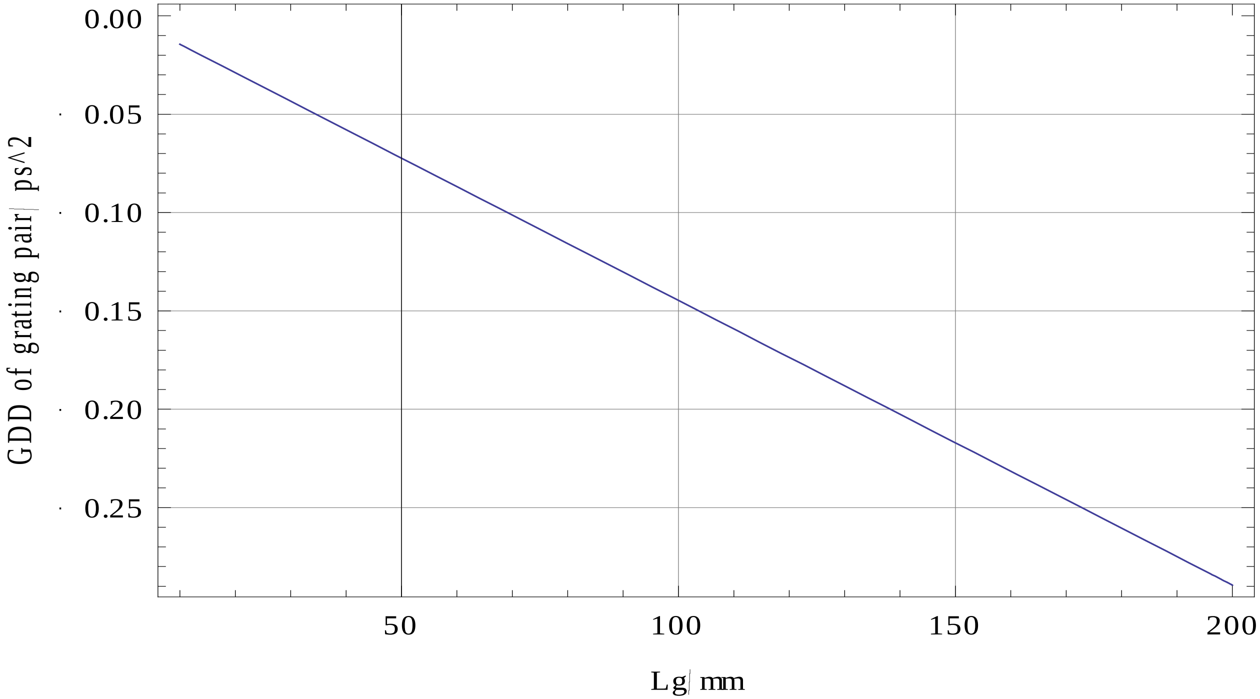
- Yb -doped fiber length ~1.5m
- Total SMF ~7.5m
- Grating distance : ~10cm
- Free space: 133cm
- Coupling rate of collimator ~55%
- SMF after Yb-doped fiber is ~3m
- SMF before Yb-doped fiber is ~5m

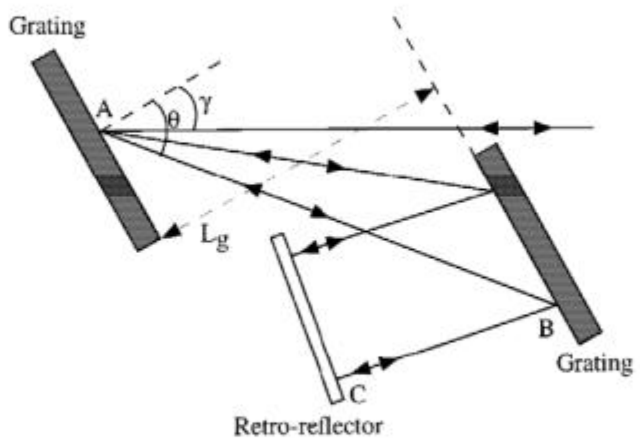
Grating pair GDD

- GDD of the fiber: 0.023ps^2/m, assume total fiber length ~7.5m. GDD of fiber is ~0.17ps^2

$$\mathrm{GDD} = \frac{-\lambda^3 * \mathrm{Lg}}{\mathrm{Pi} * c^2 * d^2} * \left(1 - \left(\frac{\lambda}{d} - \mathrm{Sin}[\gamma]\right)^2\right)^{-3/2} \qquad \gamma = 45\mathrm{Degree}$$

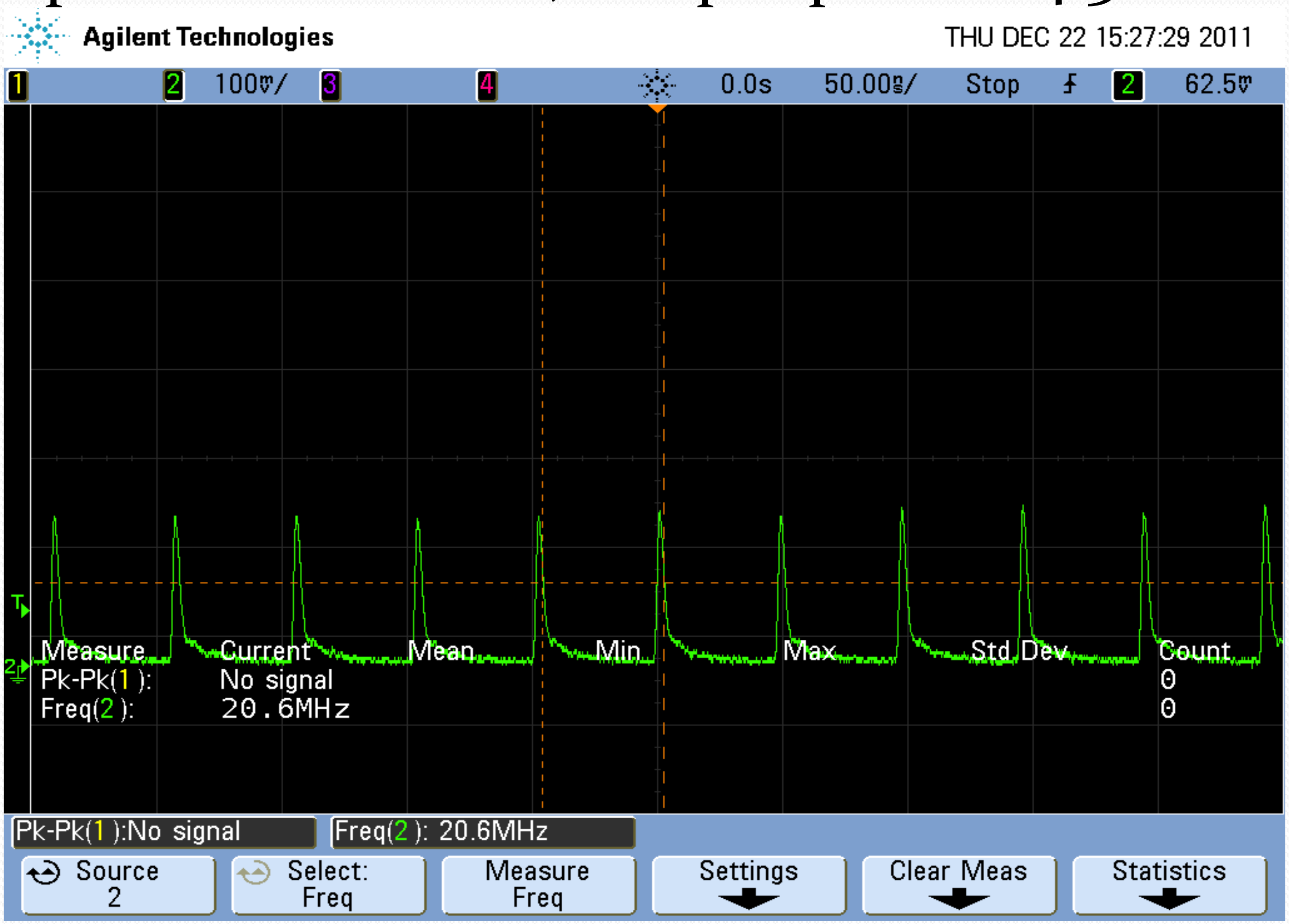
- Grating distance d~10cm





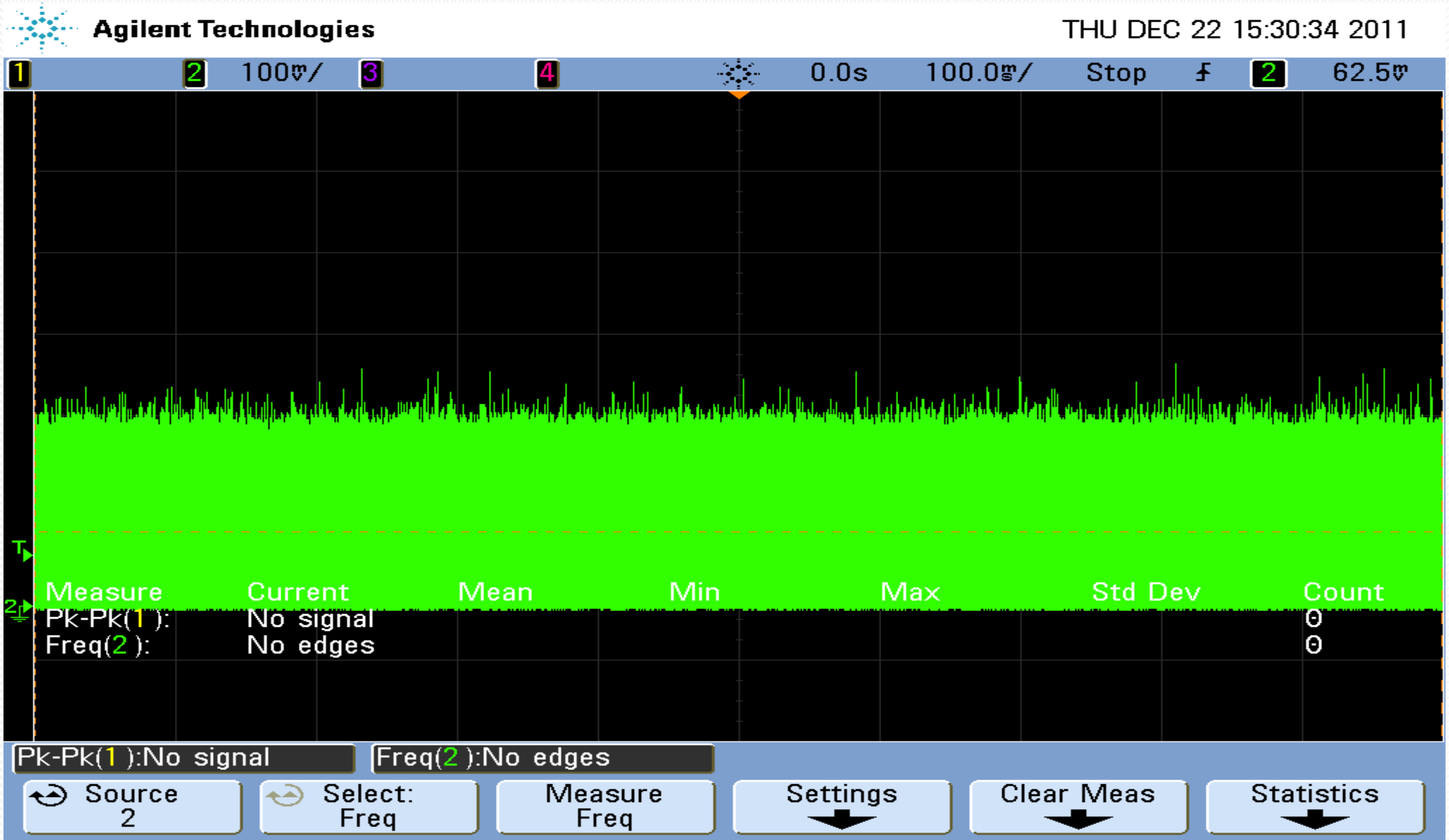
Oscilloscope trace

QWP1 64 deg, HWP 284deg, QWP2 205 deg
Pump current 2100mA, Output power 14.3mW



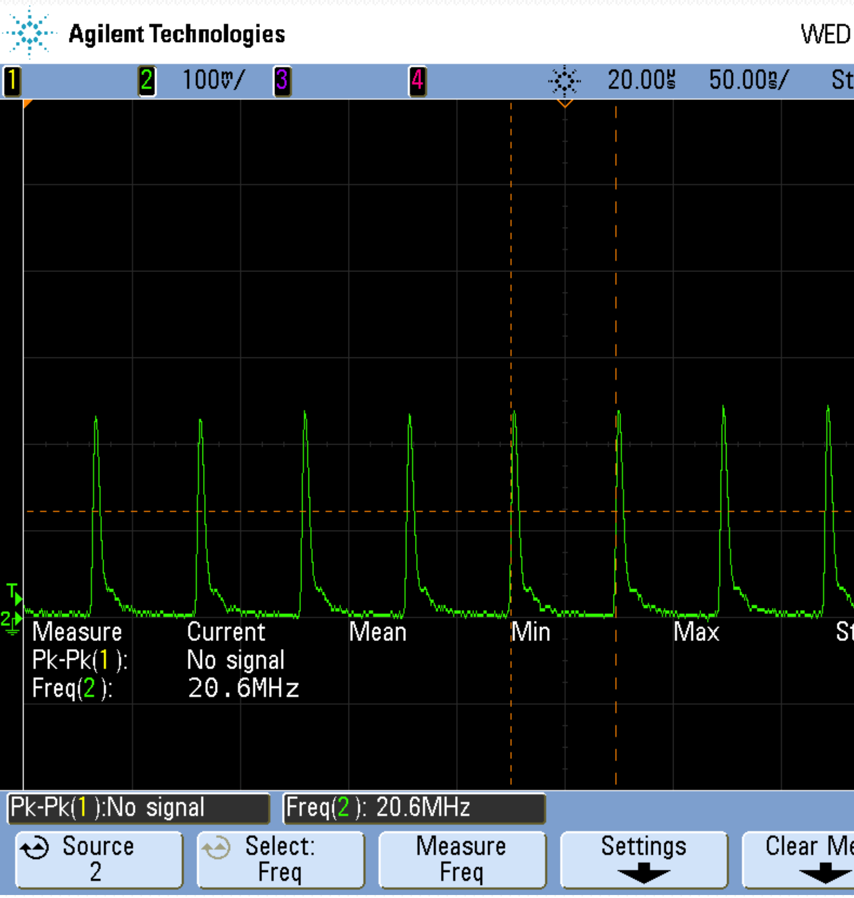
Oscilloscope trace

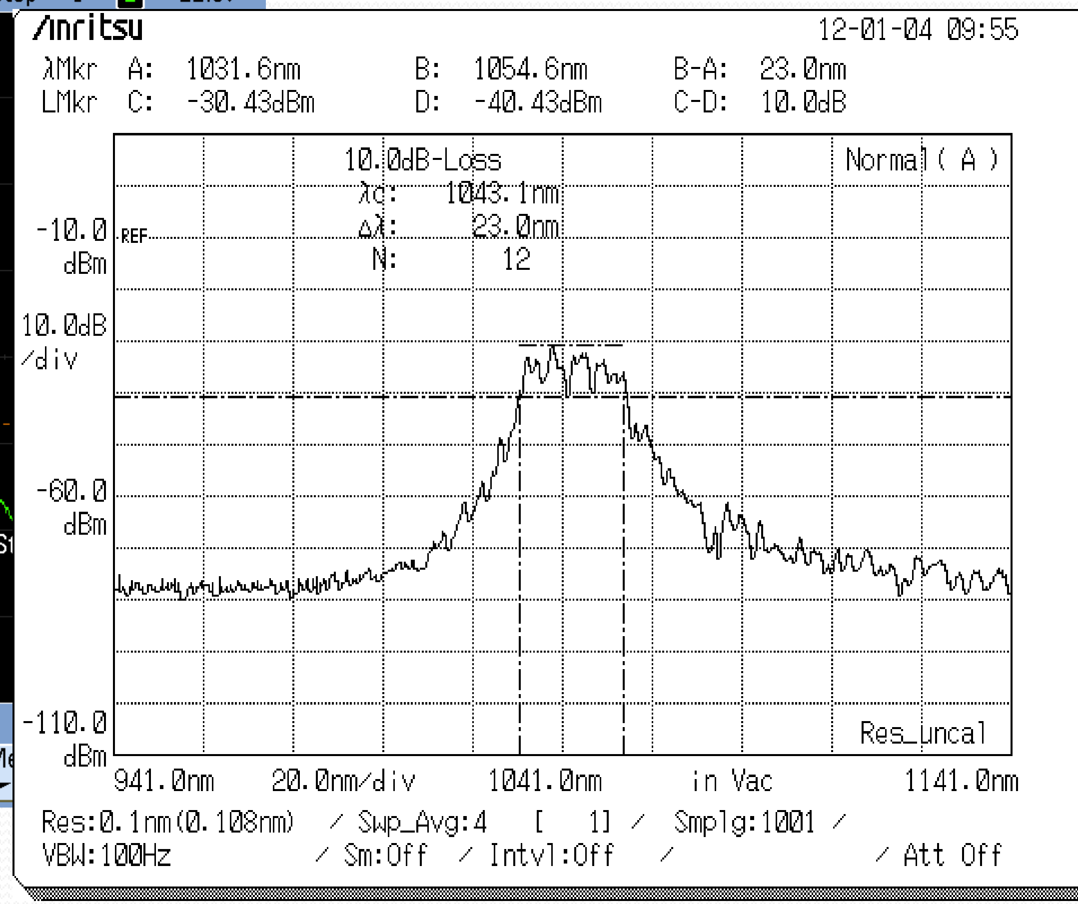
- QWP1 64 deg, HWP 284deg, QWP2 205 deg
- Pump current 2100mA， output power=14.3mW



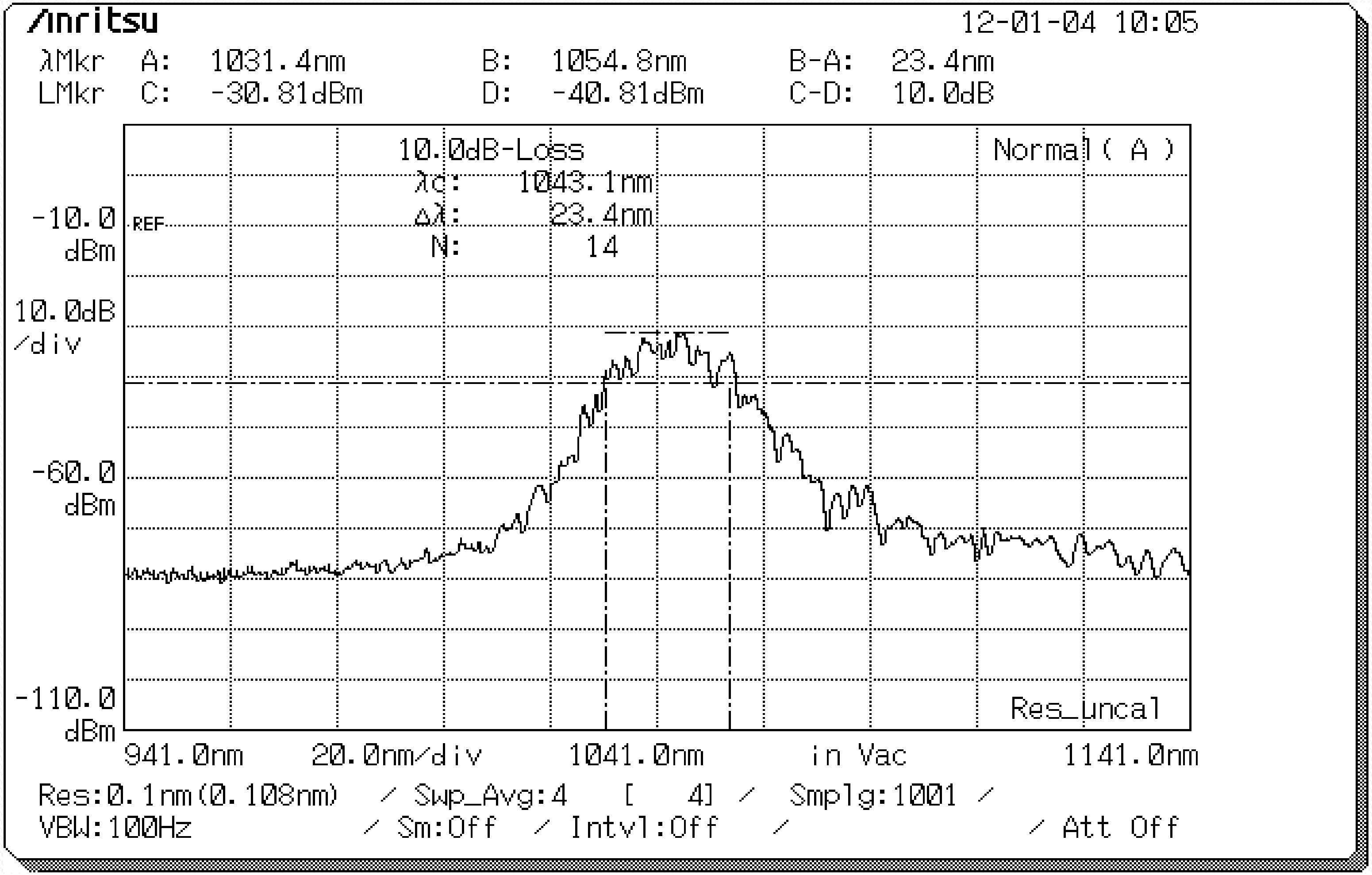
Oscilloscope trace and optical spectra

- QWP1 64 deg, HWP 255deg, QWP2 205 deg
- Pump current 2068mA, outpower 20mW

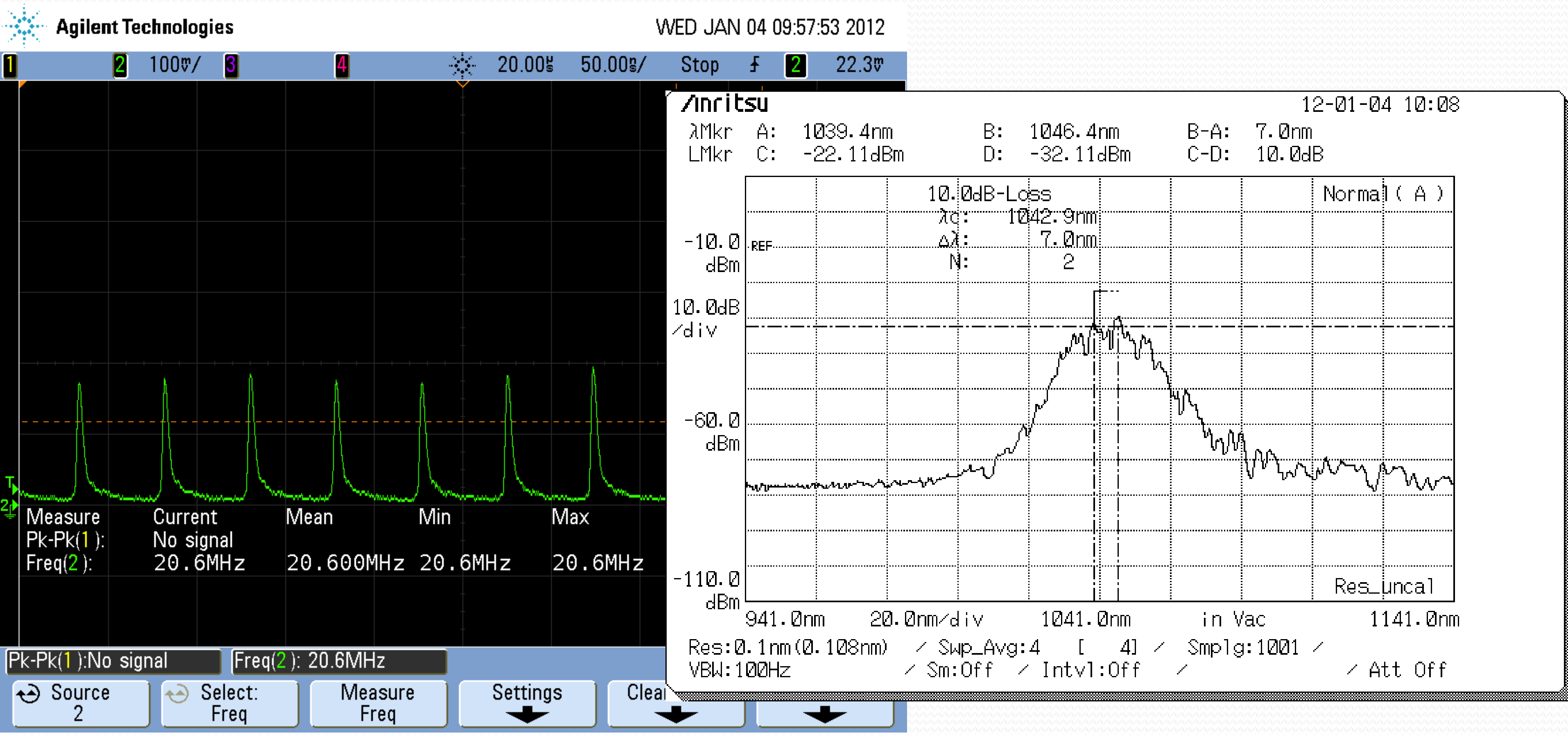




Pump current 2100mA, outpower 21mW



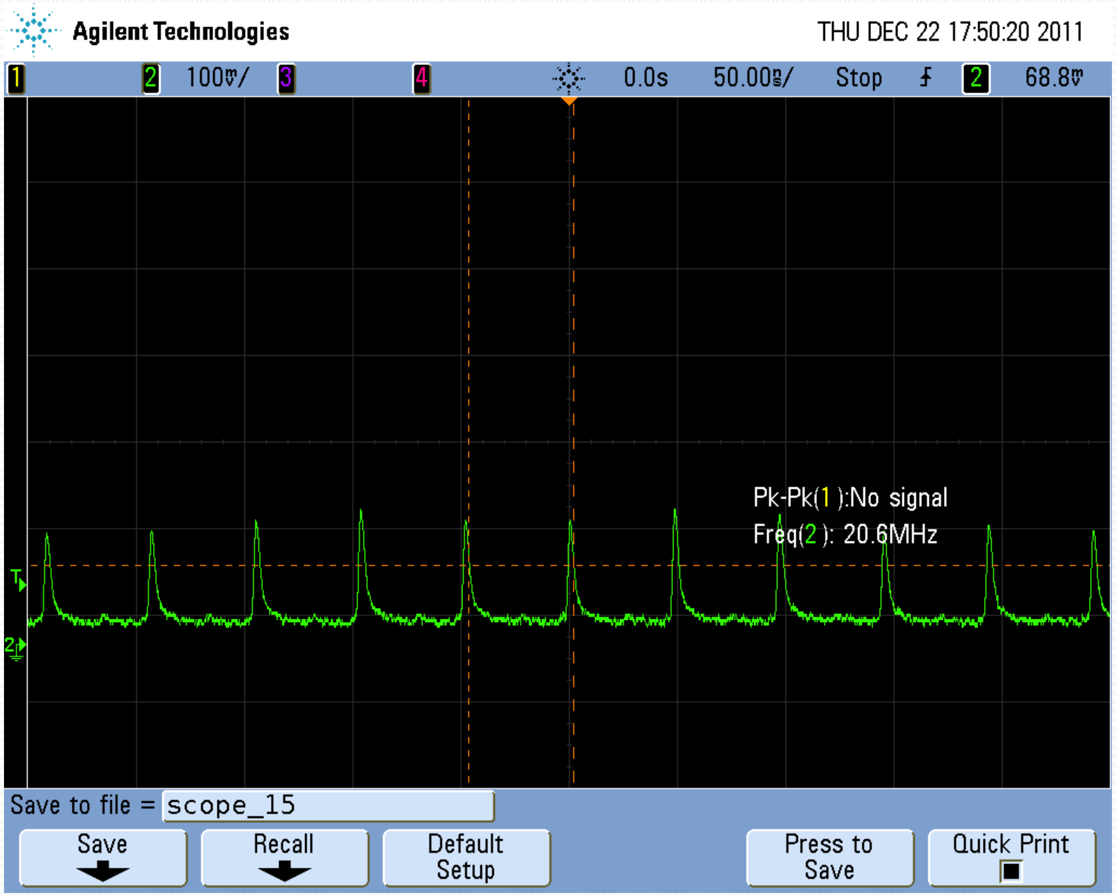
Oscilloscope trace and optical spectra



- Pump current 2200mA, outpower 24.5mW

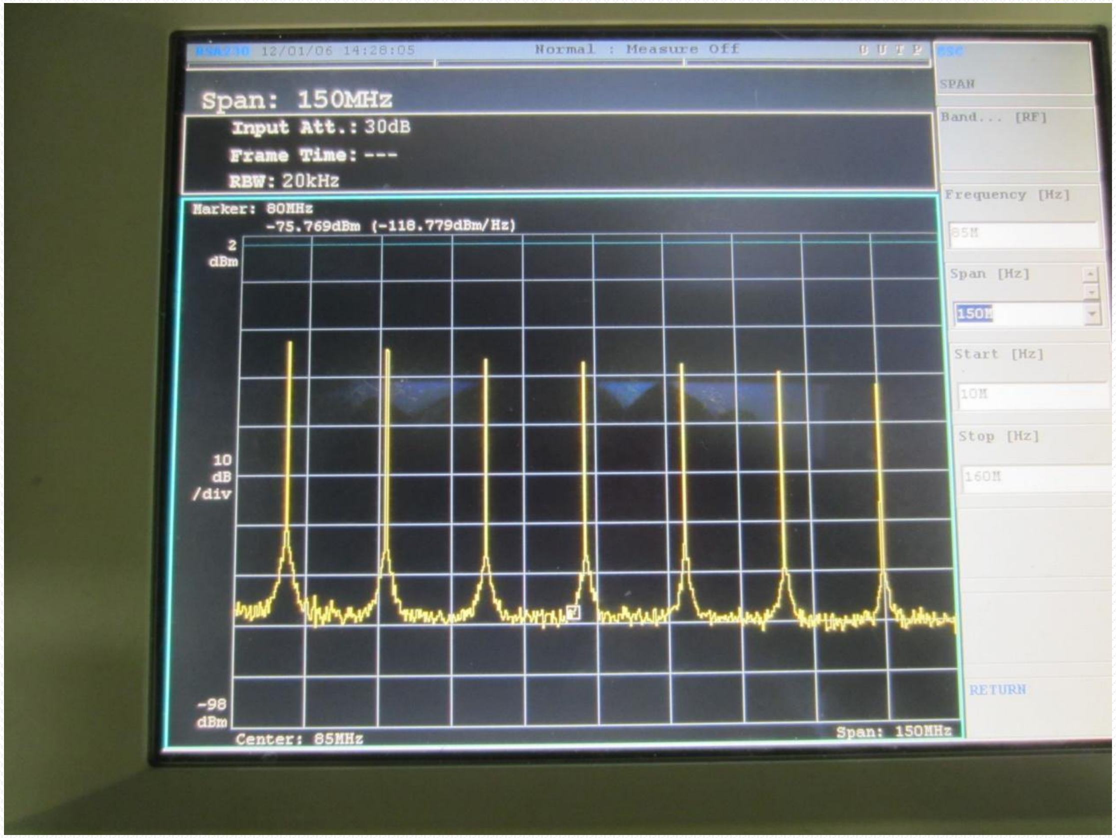
Oscilloscope trace

- Pump current 2400mA， output power=26.4mW



RF spectrum

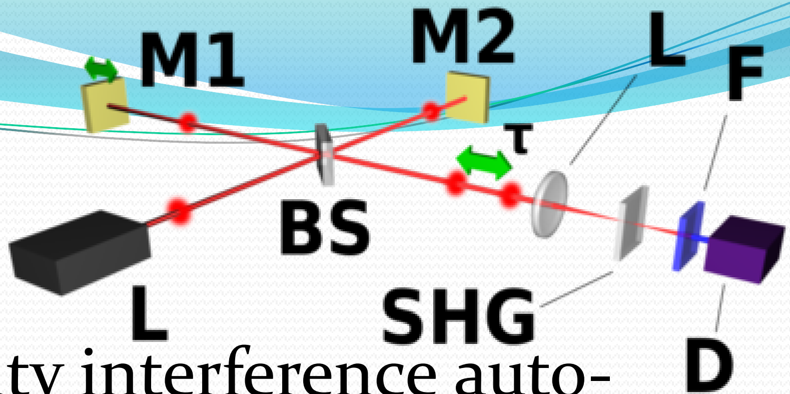
- Freq: 20.6MHz
- Signal: -17dBm,
- Noise:-70dBm



Discussion

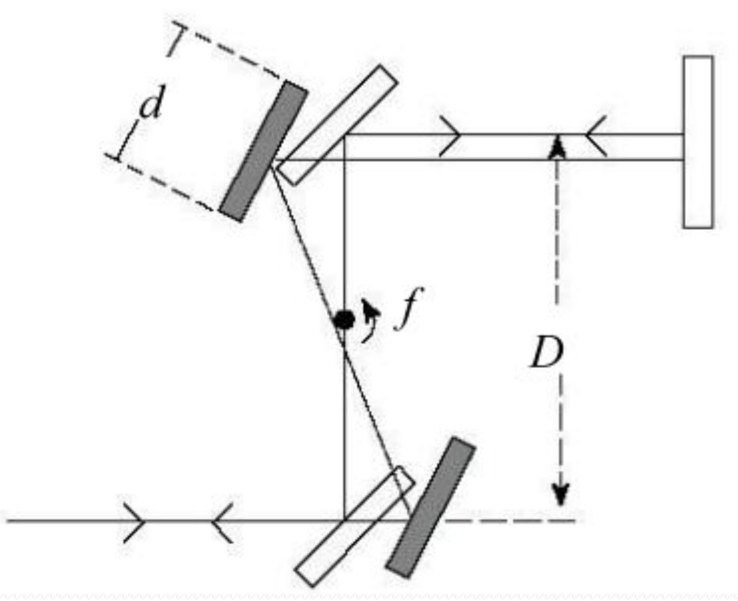
- self-starting , produce highly desirable Gaussian pulse shapes and pulse spectra
- Work in the stretched-pulse regime, with a small net normal GVD, broad spectrum bandwidth
- The output pulse characters at PBS are determined by wave plates’ positions and pump current
- stable output pulse energy ~1nJ, maximum output power ~40mW, freq~20MHz, Epulse~2nJ

Problems



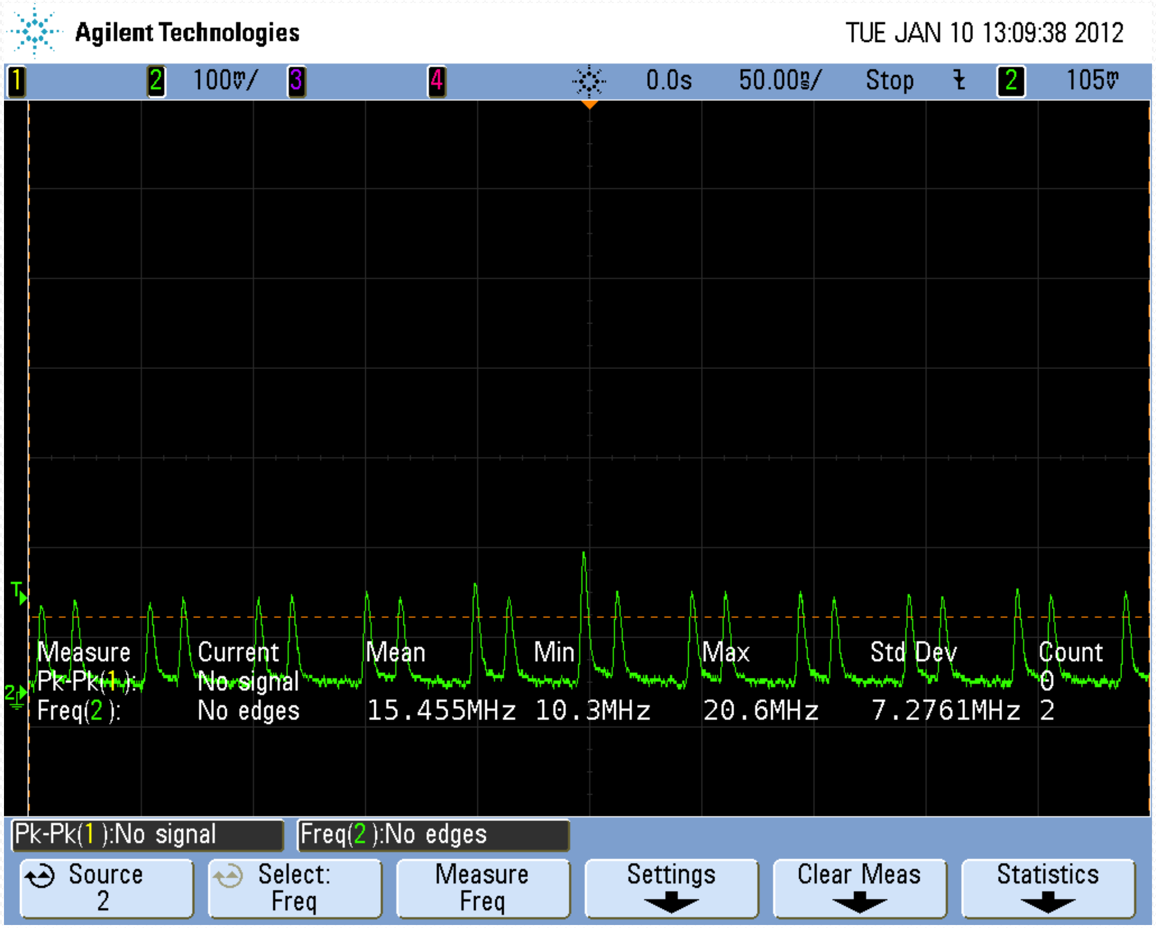
- Pulse duration measure: Intensity interference auto-correlator and FR-103XL Auto-correlator
- FR-103XL Auto-correlator : repetitive linear delay generation in one arm of the Michelson arrangement is introduced by a pair of parallel (//) mirrors centered about a rotating axis
- Fail to measure the pulse

  duration of fiber laser---SHG is t small.
- Difficult to increase the output
- power because the SMF after
- Yb-doped fiber is too long



Oscilloscope trace for pulse-breaking

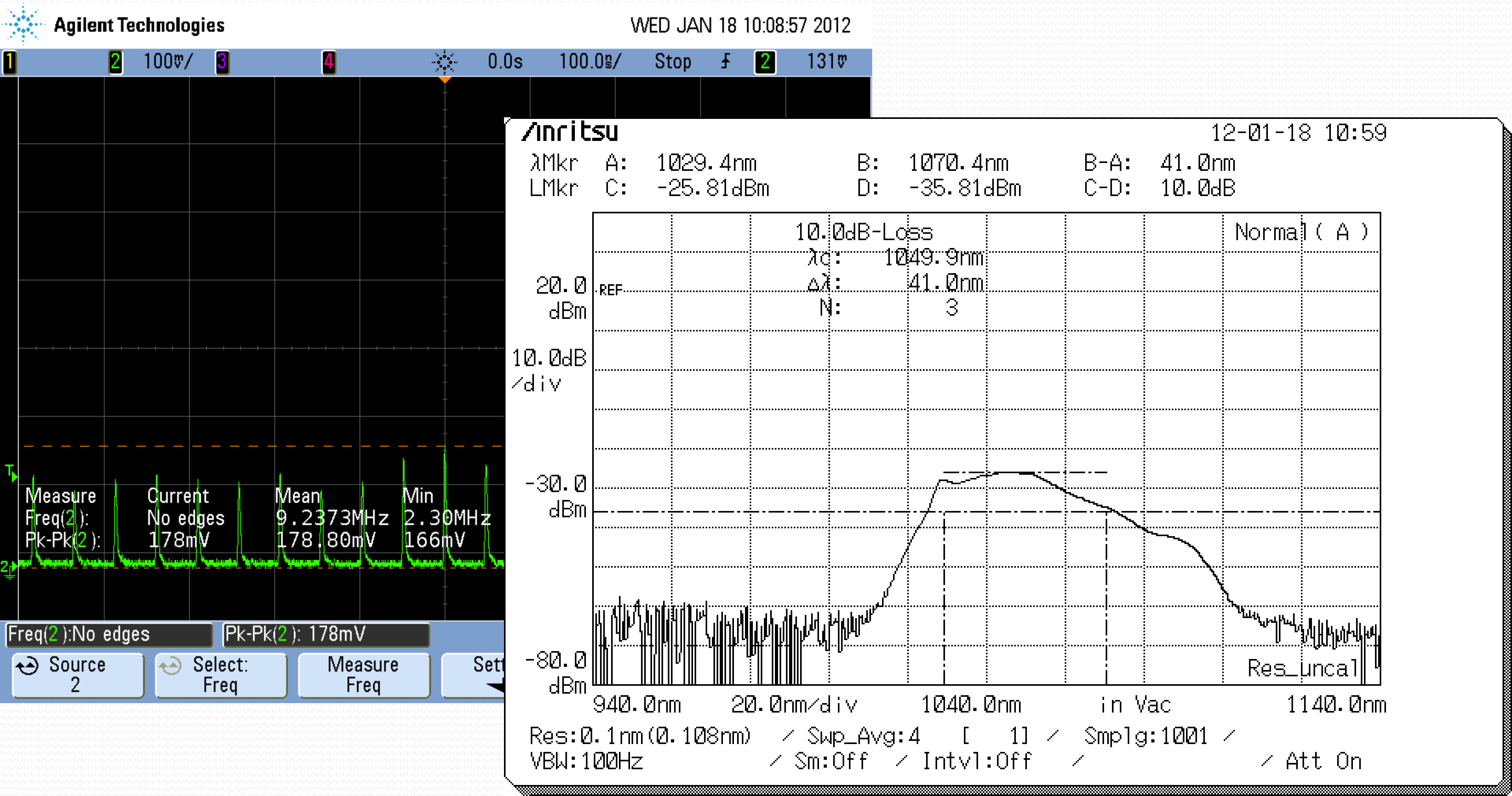
Pump current
2550mA



Excess energy result in wave breaking through the combined effects of dispersion and nonlinearity.

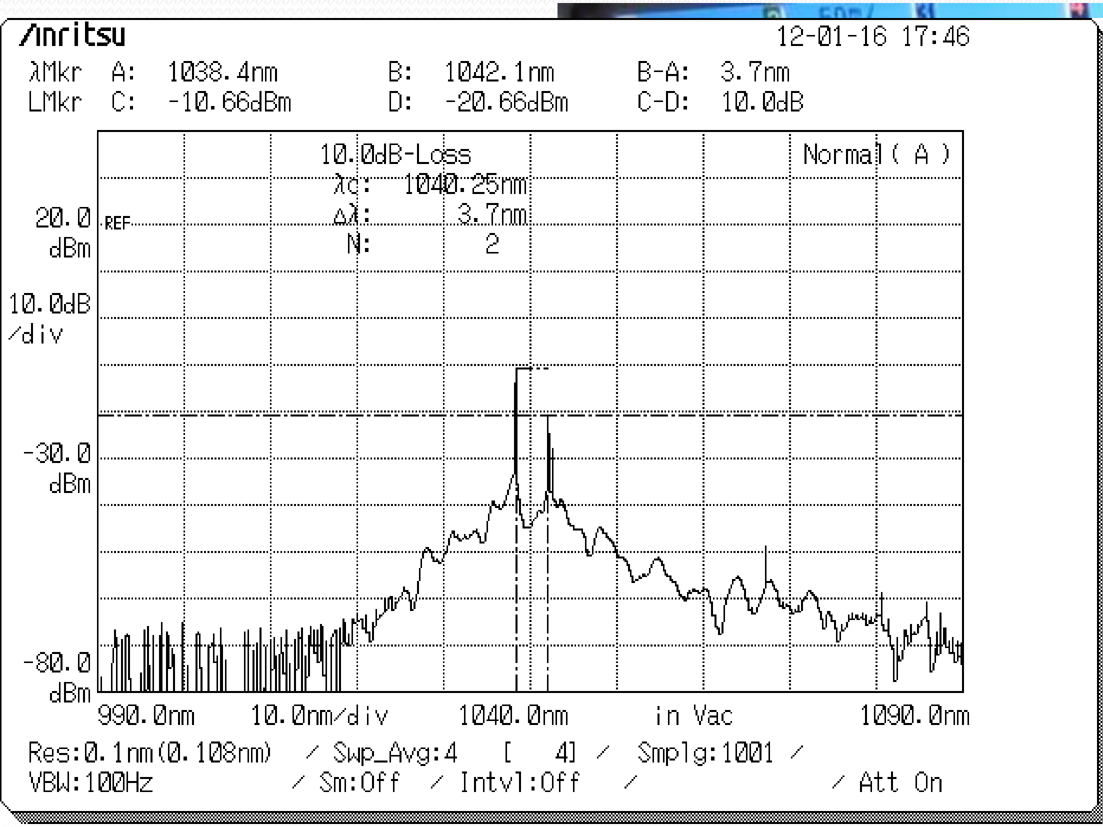
Increase pump current

- Pump current 2700mA, QWP1=260, HWP=320, QWP1=205, outpower=50mW

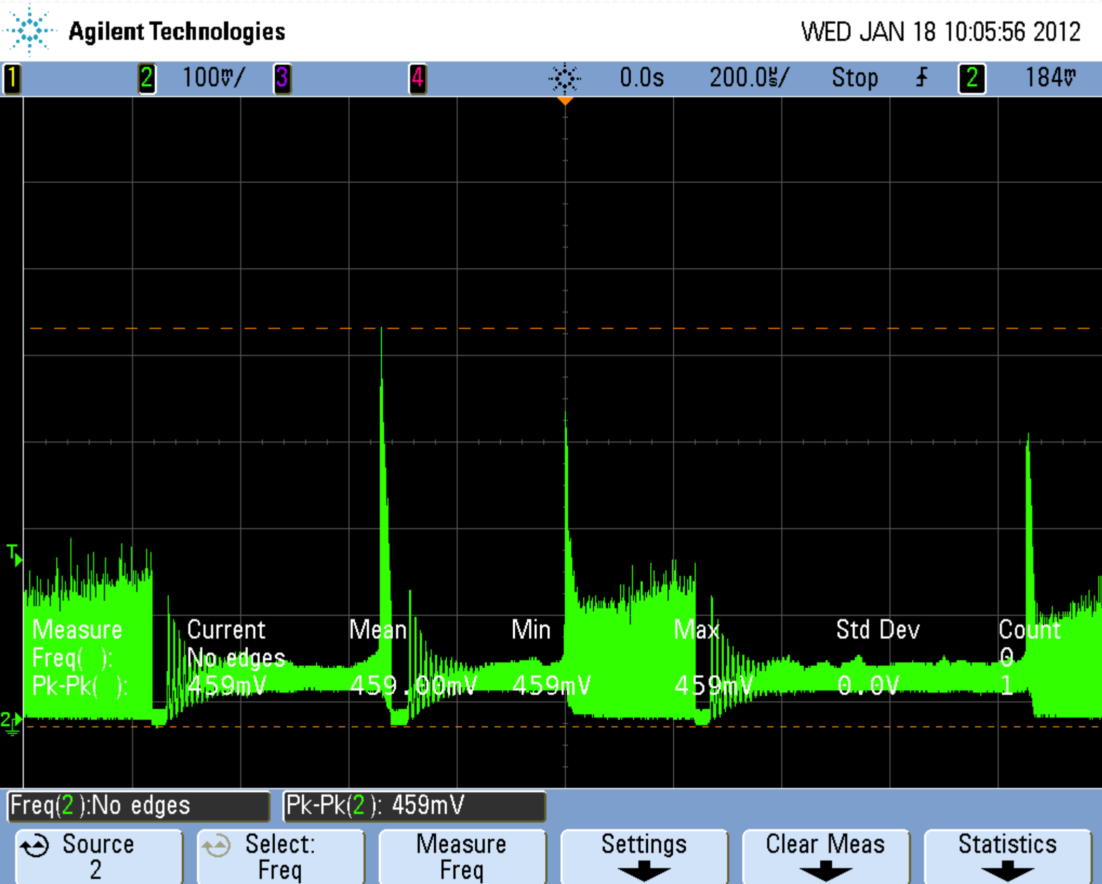


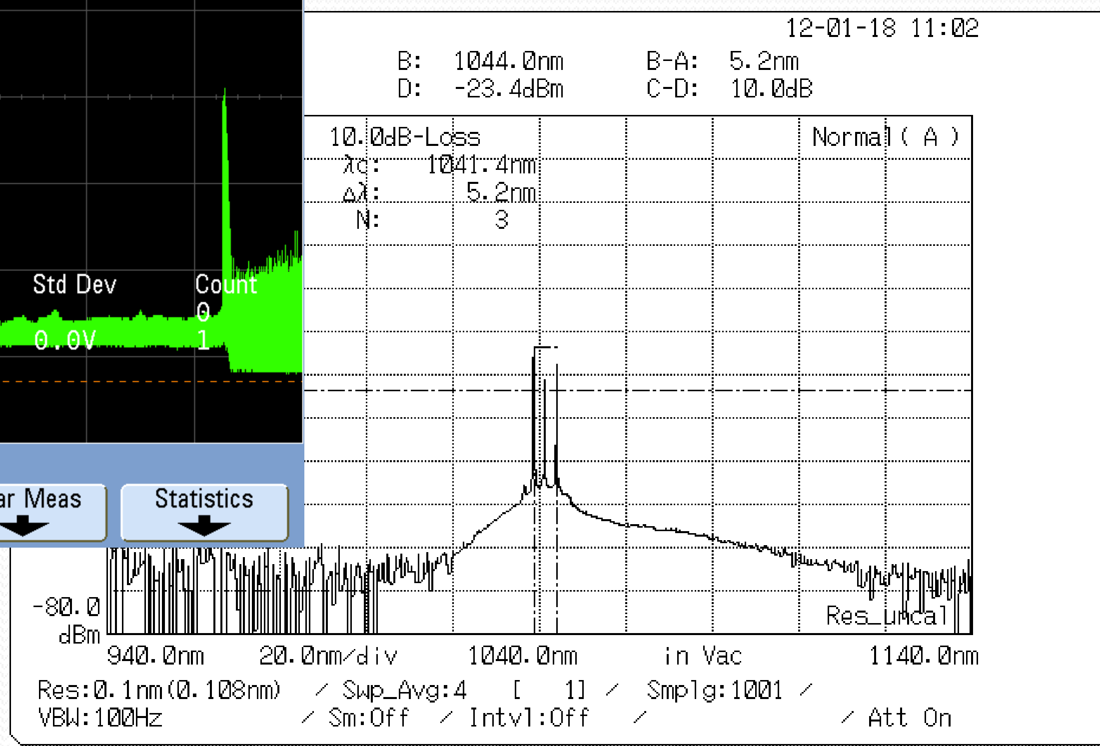
Increase pump current

Pump current 2700mA, QWP1=260, HWP=330, QWP1=205, outpower=60mW



Pump current 2700mA, QWP1=260, HWP=298, QWP1=205, outpower=100mW





Unequal pulse intensity

- With the increasing of output power, the amplitude of the pulses become unequal.
- spectrum bandwidth become narrower, with the increase of output power, even with spikes
- Reason: Over driving NLPR? Nonlinearity too strange?
- Impossible to increase the output power in the current setup

Drawbacks of my setup

- Splice loss is still too large
- The SMF after the Yb-doped fiber too long: amplified pulse propagates through this part of SMF accumulate a lot of nonlinearity, which impose a major limitation on the highest energy
- Yb-doped fiber too long, nonlinearity cannot be neglected
- Distance between the grating can not be tuned, for the fixed stages
- Grating reflectivity is a little lower
- ....

How to increase the out power

- Change the stage of the grating to tune the distance of the fiber
- Shorten the SMF before the Yb-doped fiber, which is the main reason for low power output.

References

- 2004, F. O . Ilday, Self-Similar Evolution of Parabolic Pulses in a Laser
- 2005, J. R. Buckley, Femtosecond fiber lasers with pulse energies above 10 nJ
- 2006, Andy Chong,All-normal-dispersion femtosecond fiber laser
- 2008, W. H. Renninger,Dissipative solitons in normal-dispersion fiber lasers

Thank you!