Optical Short Pulse Generation and Measurement Based on Fiber Polarization Effects

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Applications of Optical Pulse Train

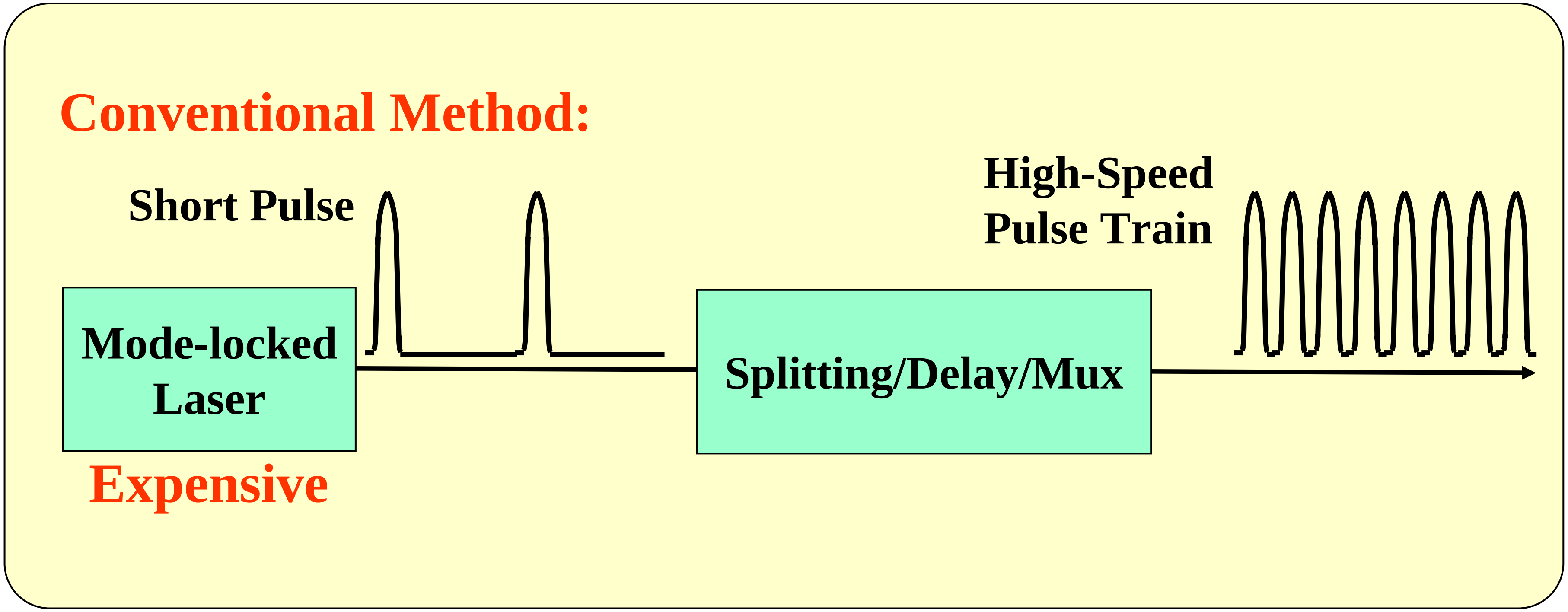
- Return-to-zero (RZ) and carrier-suppressed RZ (CSRZ) modulation formats can be created from pulse trains.
- RZ and CSRZ have been shown to be robust to fiber-based degrading effects for many high-speed, long-distance transmission systems.
- Other applications: high speed optical time division multiplexing (OTDM), all-optical regeneration and optical sampling.

- Cost-effective, high speed, chirp-free RZ and CSRZ pulse train generation is desired.

Outline

1. Introduction
2. Multi-Channel 40-GHz Optical Pulse Train Generation
3. Multi-Channel 160-GHz Optical Pulse Train Generation
4. Measurement of Pulse Width of Short Pulses
5. Summary

High-Repetition-Rate Pulse Train Generator



- Mode-locked laser is expensive equipment.
- Single channel.
- The tuning range of the wavelength is limited.

High speed Optical Pulse Train Generation

Prior Work

- Electro-absorption (EA) modulator: high extinction ratio and multi-channel operation are hard to achieve and expensive drive electronics is required.

- Fiber based optical parametric amplification (OPA) to convert a pulsed pump source at a fixed wavelength into a pulsed signal at a tunable idler wavelength: requires a very high power EDFA.

Pulse Train Generation Based on MZM

Prior Work

- **Electro-optical (E-O) Mach-Zehnder intensity modulator (MZM) driven by an electrical clock with peak-to-peak voltage value of V_π at the desired data rate: requires the use of a high-speed intensity modulator and driver for RZ generation.**

- **MZM driven at half the bit rate but with a peak-to-peak voltage value of $2V_\pi$ with different biases: the high peak-to-peak voltage is difficult to achieve at high frequency.**

- **Dual-driven MZM which requires two sets of electrical drivers.**

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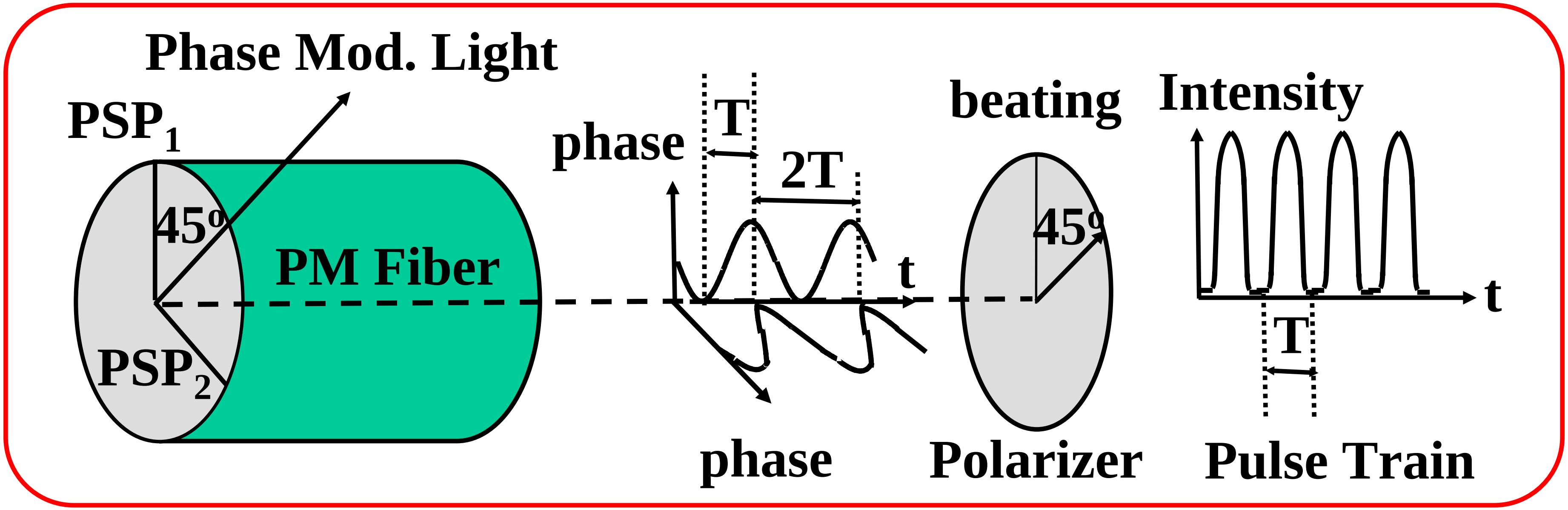
Pulse Train Generation Based on Phase Modulator

- **We demonstrate 40-GHz optical pulse train generation by employing an E-O phase modulator that is driven by a clock at only half the bit rate and a peak-to-peak voltage value of V_π, with a polarization-maintaining (PM) fiber as interferometer.** ***(C. Yu et al., PTL 2006.)***

- **We extend this technique for WDM applications and demonstrate ITU-grid multi-channel high-speed optical pulse train generation by using a single set of phase modulator and PM fiber.** ***(C. Yu et al., CLEO 2007.)***

- **Advantages: cost-effective and seamlessly integrated with optical fiber systems, and has no high-power requirement.**

Concept of Pulse Generation Using a Phase Modulator and PM Fiber



- After half-frequency (20-GHz) sinusoidal phase modulation, the light is split equally into the two principal-states-of-polarization (PSPs) of the PM fiber. Differential group delay (DGD) provides a one-bit time shift (*T=25 ps*) between the two polarization components of the light.
- At the output of the PM fiber, due to beating of the two replicas of the light, one polarization, aligned 45º with respect to the PSPs, generates an 40-GHz RZ pulse train, whereas the orthogonal polarization generates a 40-GHz CSRZ pulse train.

Calculation of 40-GHz Pulse Generation

The optical fields of these two replicas after the PM fiber:

PSP1: $$E_1 = \frac{A}{\sqrt{2}}\cos\left(\frac{\pi}{2}\sin\frac{\pi t}{T} + \omega t\right)$$

PSP2: $$E_2 = \frac{A}{\sqrt{2}}\cos\left[\frac{\pi}{2}\sin\frac{\pi(t-T)}{T} + \omega t\right] = \frac{A}{\sqrt{2}}\cos\left(-\frac{\pi}{2}\sin\frac{\pi t}{T} + \omega t\right)$$

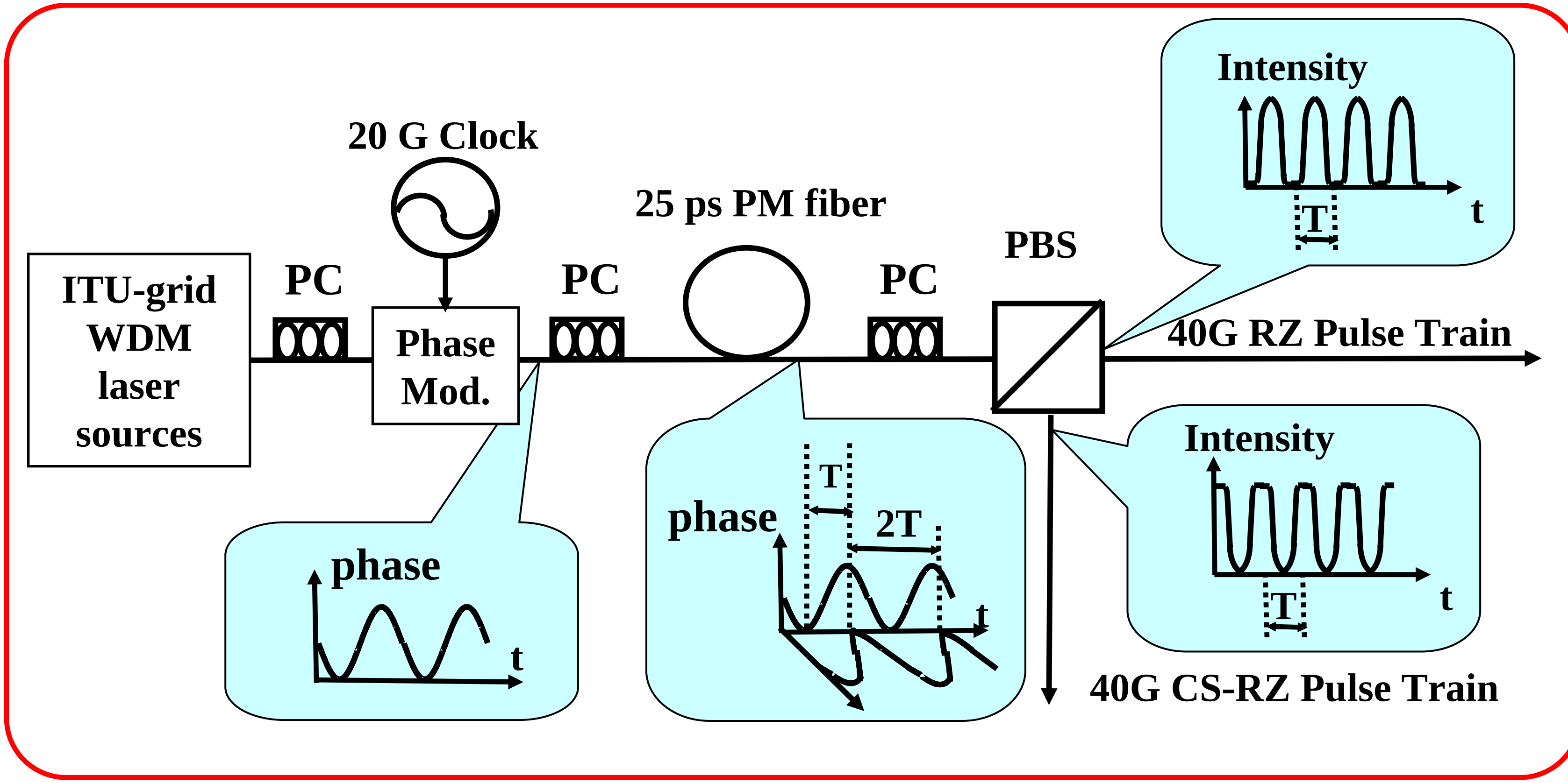
when $\omega T = k\pi$ **and k is an integer. After a polarizer:**

+45º to PSPs (33%RZ): $$E_3 = \frac{E_1 + E_2}{\sqrt{2}} \propto A\cos\left(\frac{\pi}{2}\sin\frac{\pi t}{T}\right)\cos(\omega t)$$

-45º to PSPs (67% CSRZ): $$E_4 = \frac{E_1 - E_2}{\sqrt{2}} \propto A\sin\left(\frac{\pi}{2}\sin\frac{\pi t}{T}\right)\sin(\omega t)$$

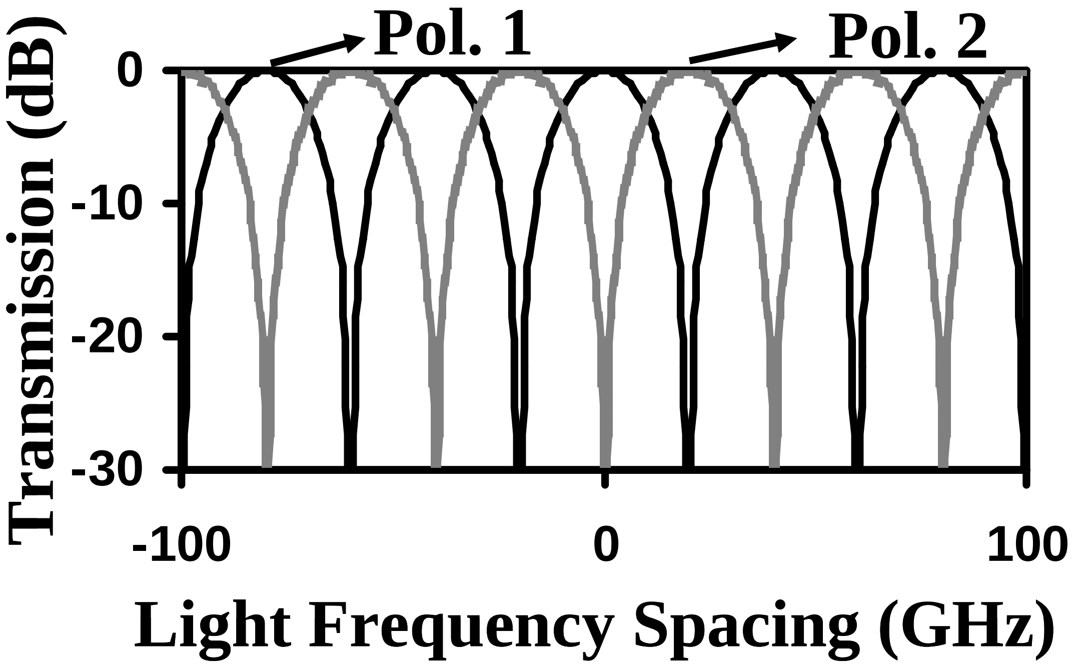
- **For 40 GHz pulse generation, *f=40 GHz* and *T=1/f=25 ps*.**
- **The generated pulse trains are chirp free.**

Experimental Setup



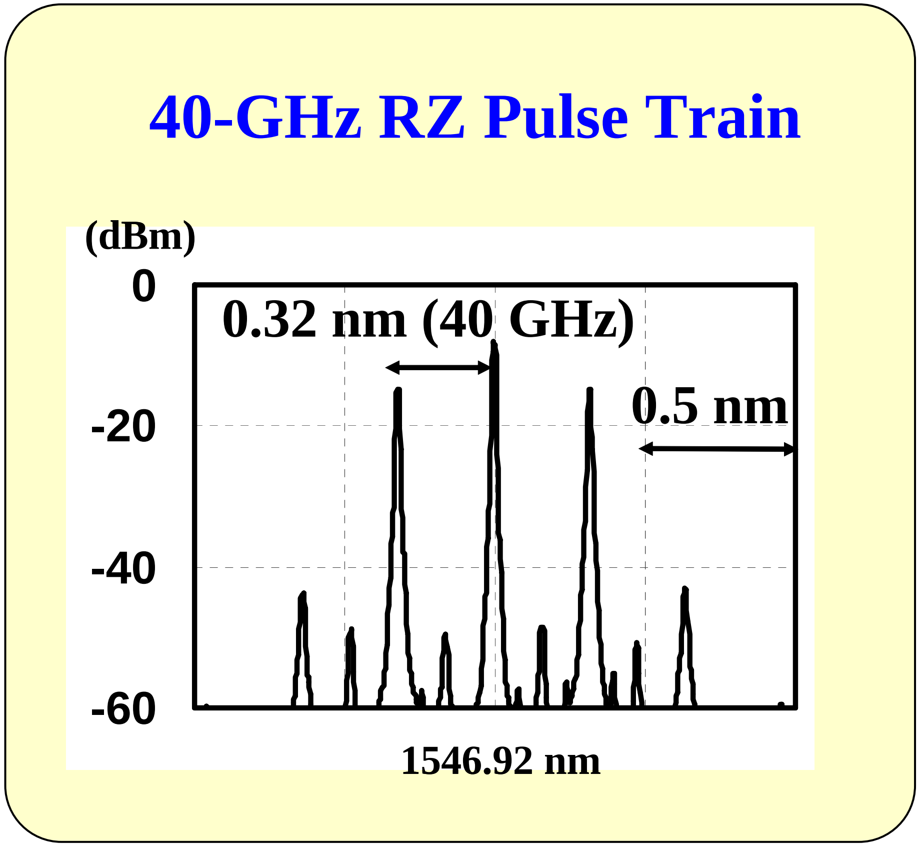
- A polarization controller (PC) is used to align the light to be along the direction of 45^{o} to the PSPs of the PM fiber.
- Another PC is used to align the polarization beam splitter (PBS) to also be 45^{o} to the PSPs of the PM fiber.

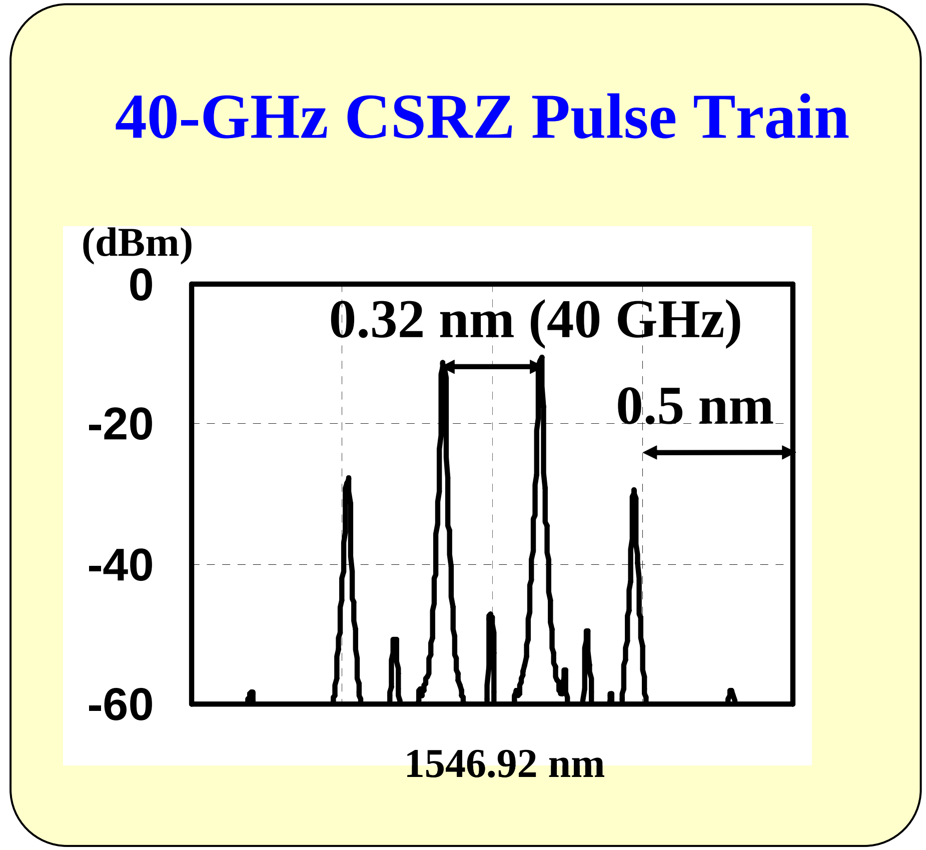
Transmission Spectrum of the Interferometer



- Note that PM fiber with PBS works as one-bit delay (*T=25 ps*) interferometer with a FSR of *1/T* (40 GHz). Therefore, the channel spacing should be integral times of 20 GHz, which matches the 100-GHz-channel-spacing ITU-grid DWDM systems.

Optical Spectra (Channel 193.8 THz)

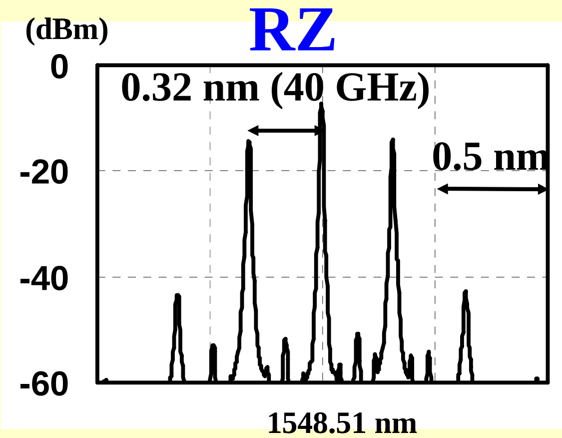


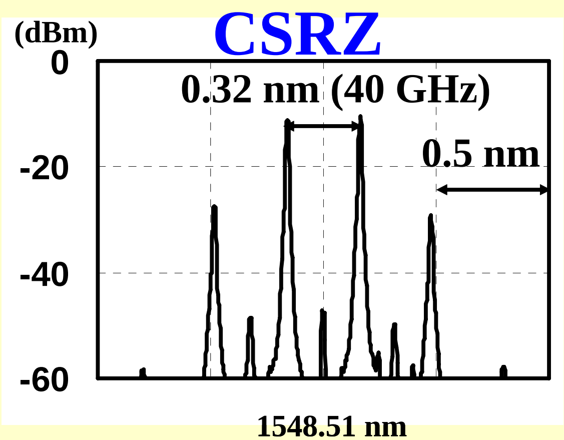


- In our experiment, 4-channel ITU grid lights with a channel spacing of 200 GHz are launched into the system at the wavelengths of 1546.92 nm (193.8 THz), 1548.51 nm (193.6 THz), 1550.12 nm (193.4 THz), and 1551.72 nm (193.2 THz).

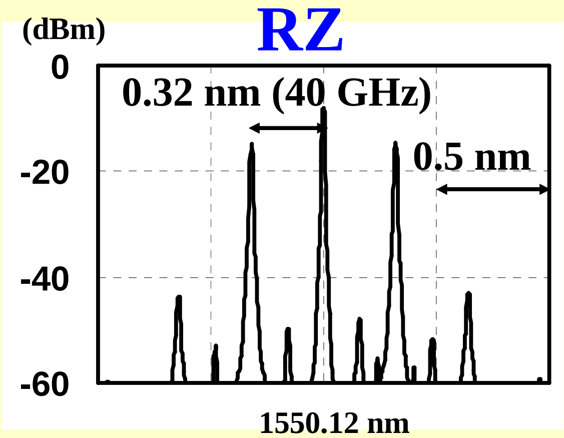
Optical Spectra (The Other 3 Channels)

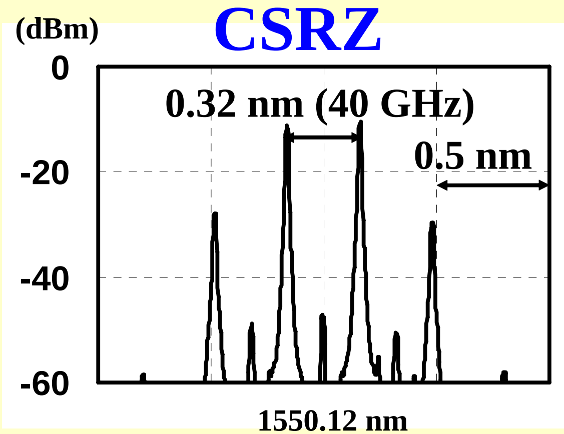
Channel 193.6 THz



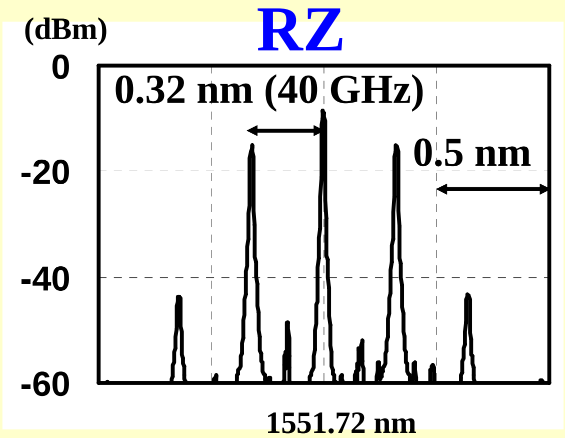


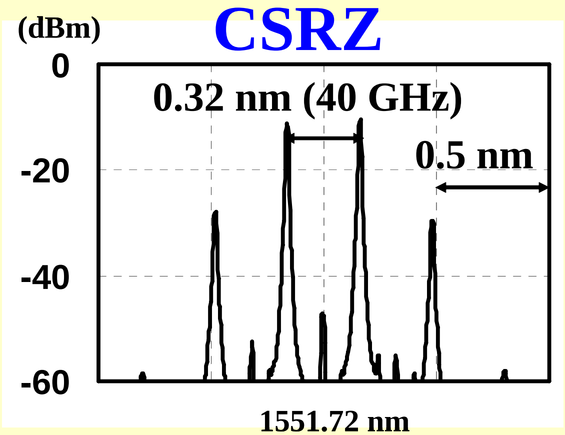
Channel 193.4 THz





Channel 193.2 THz

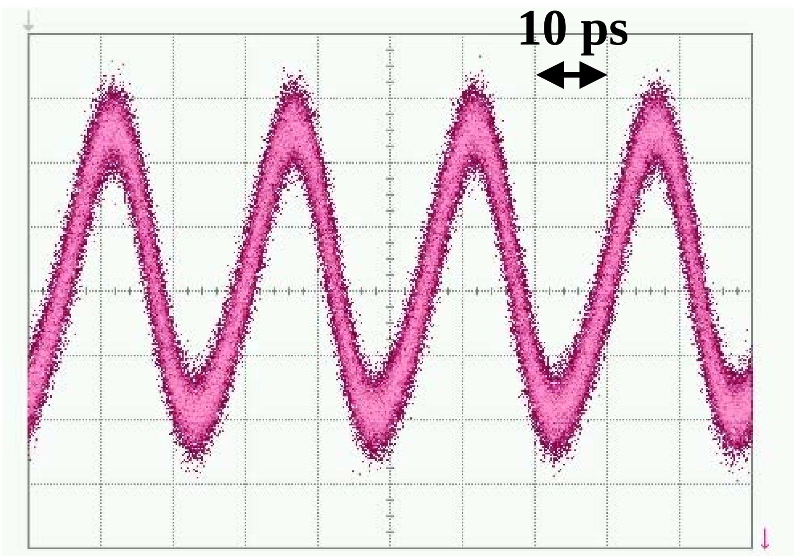




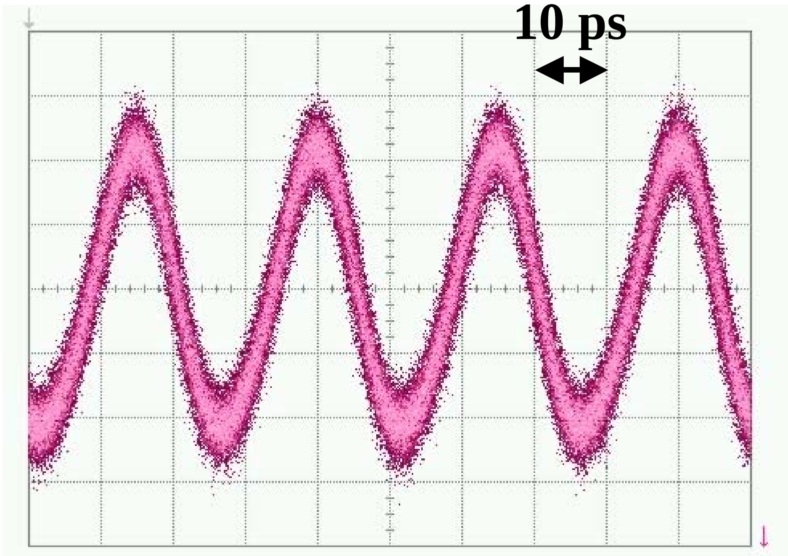
- The unwanted 20 GHz tones of RZ are suppressed by > 30 dB.
- The optical carriers of CSRZ are suppressed by > 35 dB.

Waveforms of the Generated RZ and CS-RZ Pulse Trains (Channel 193.6 THZ)

40-GHz RZ Pulse Train



40-GHz CSRZ Pulse Train



- **The observed waveforms of 33% RZ and 66% CSRZ look similar due to the bandwidth limitation of the photodiode.**

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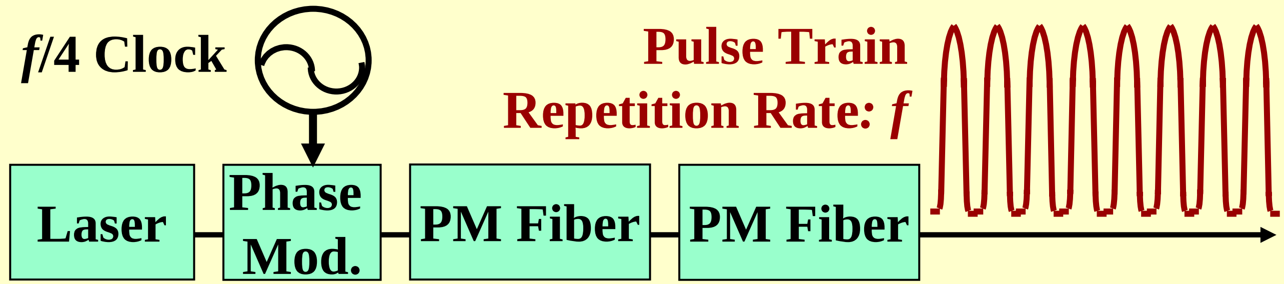
ITU-grid multi-channel 160-GHz Pulse Train Generation Based on Phase Modulator

Our Method:

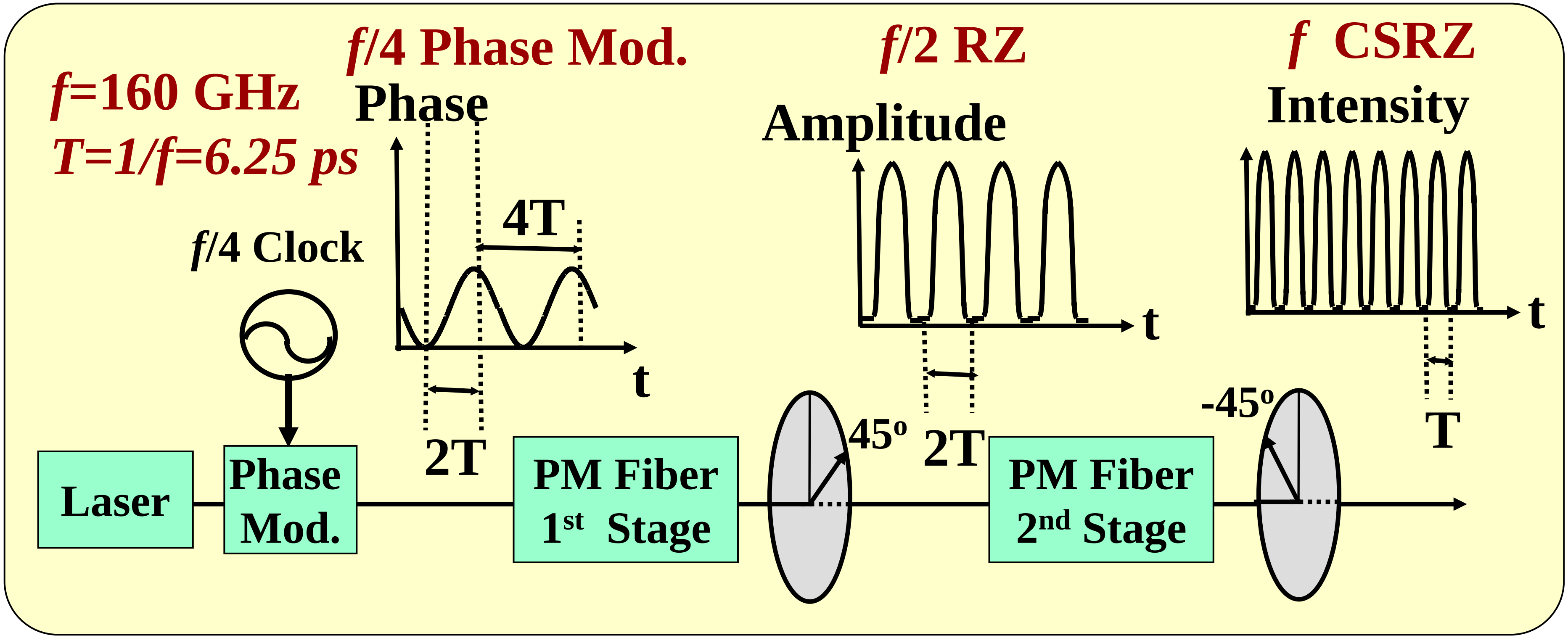


- Low cost
- Easy operation
- Seamlessly integrated with fiber systems
- No high-power requirement

- We demonstrate single-channel 160-GHz optical pulse train generation by employing a phase modulator with two stages of PM fiber.
- We then extend this technique for WDM applications and demonstrate ITU-grid multi-channel 160-GHz optical pulse train generation.

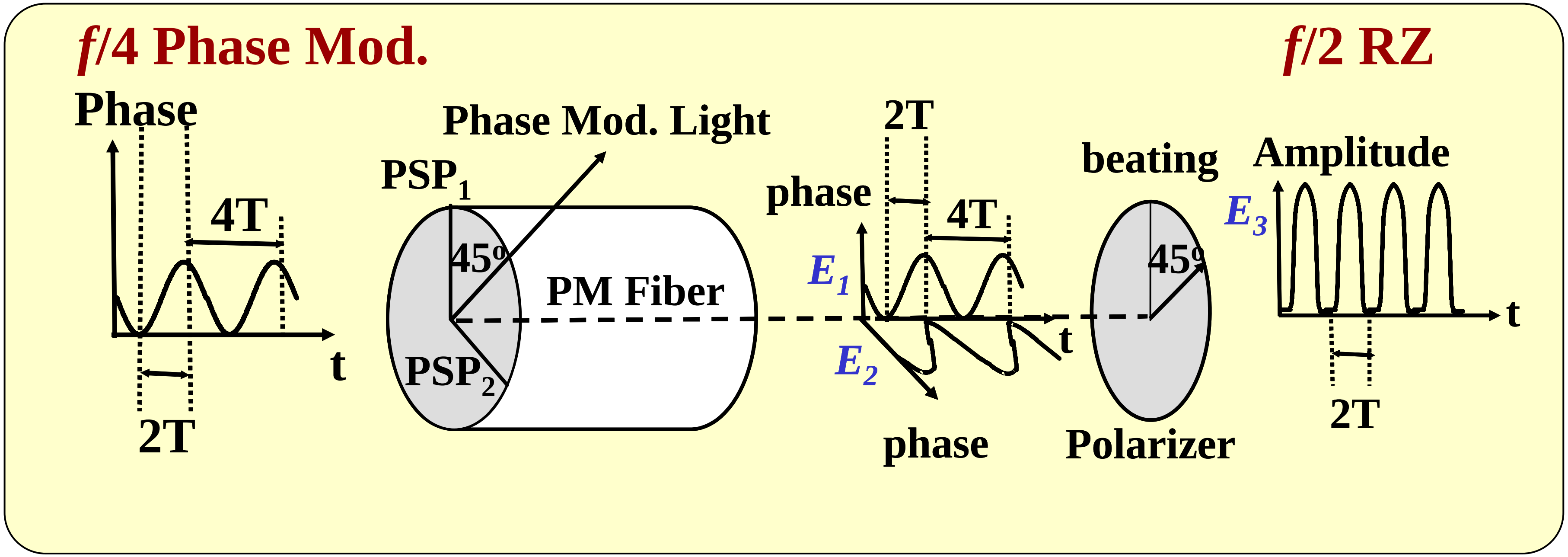
C. Yu et al., ICICS 2007

160-GHz Pulse Generator Using a 40-GHz Phase Modulator and PM Fiber



- An 80-GHz optical RZ pulse train is generated by constructive beating of a 40-GHz phase modulated light at the first stage.
- A 160-GHz optical CSRZ pulse train is generated by destructive beating of the two replicas of the light at the second stage.

1^{st} Stage: *f*/4 Phase Mod.→ *f*/2 RZ Pulse Train



- DGD of PM fiber makes a two-bit time (2T) shift between the two replicas (E_1 and E_2) of the light.
- After the polarizer, the components of E_1 and E_2 constructive beat with each other and produce: $E_3 \propto (E_1 + E_2)$.
- E_3 is chirp-free 33% RZ pulse train at a repetition rate doubling the frequency of phase modulation.

1^{st} Stage: *f*/4 Phase Mod.→ *f*/2 RZ Pulse Train

After PM Fiber (When $\omega T = k\pi$):

(For 160G pulse generation, *f*=160 GHz and T=1/*f*=6.25 ps)

$$E_1 = \frac{A}{\sqrt{2}}\cos(\frac{\pi}{2}\sin\frac{\pi t}{2T} + \omega t);$$ ***(f/4=40G Phase Modulation)***

$$E_2 = \frac{A}{\sqrt{2}}\cos\left[\frac{\pi}{2}\sin\frac{\pi(t-2T)}{2T} + \omega t\right] = \frac{A}{\sqrt{2}}\cos(-\frac{\pi}{2}\sin\frac{\pi t}{2T} + \omega t)$$

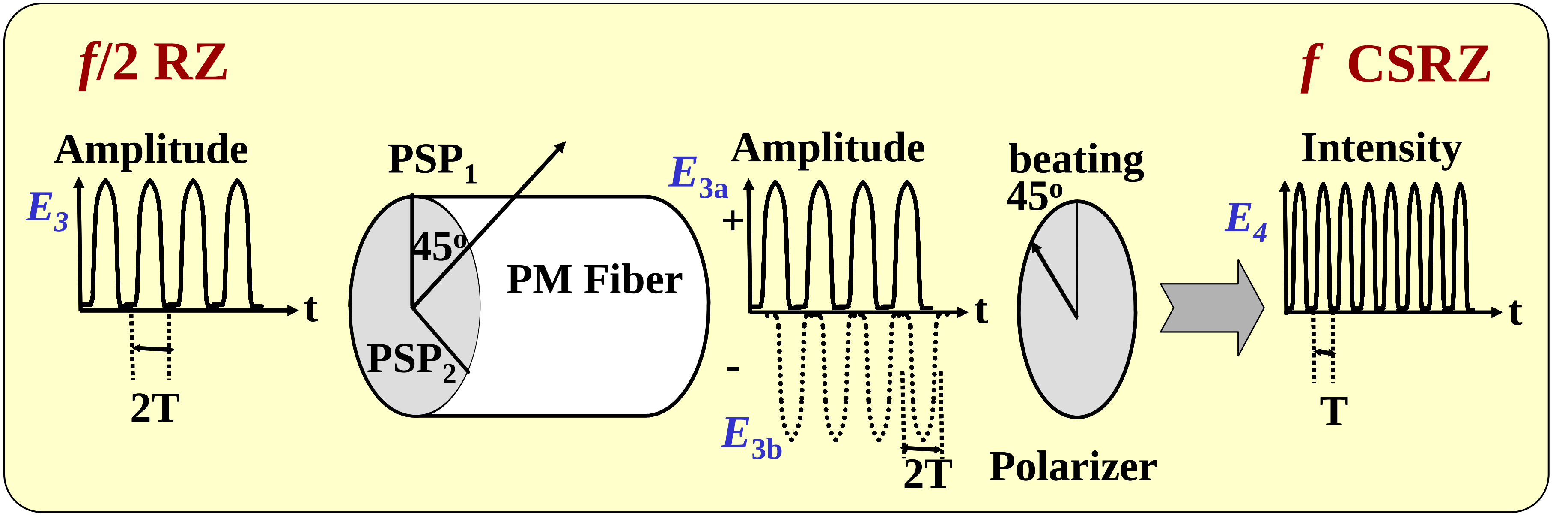
After Polarizer:

(by constructive beating of a 40-GHz phase modulated light)

$$E_3 = \frac{E_1 + E_2}{\sqrt{2}} \propto A\cos(\frac{\pi}{2}\sin\frac{\pi t}{2T})\cos(\omega t)$$

(f/2 = 80GHz chirp-free 33% RZ pulse train)

2^{nd} Stage: $f/2$ RZ → f CSRZ Pulse Train



- **DGD of PM fiber makes a one-bit time (T) shift between the two replicas (E_{3a} and E_{3b}) of the light.**
- **After the polarizer, the components of E_{3a} and E_{3b} destructive beat with each other and produce: $E_4 \propto (E_{3a} – E_{3b})$.**
- **E_4 is chirp-free 50% CSRZ pulse train at a repetition rate doubling the repetition rate of E_3.**

2nd Stage: *f*/2 RZ → *f* CSRZ Pulse Train

After 2nd PM Fiber (When $\omega T = 2k\pi$):

(For 160G pulse generation, *f*=160 GHz and T=1/*f*=6.25 ps)

$$E_{3a} \propto A\cos\left(\frac{\pi}{2}\sin\frac{\pi t}{2T}\right)\cos(\omega t)$$

(f/2 = 80 GHz RZ pulse train)

$$E_{3b} \propto A\cos\left[\frac{\pi}{2}\sin\frac{\pi(t-T)}{2T}\right]\cos(\omega t) = A\cos\left(\frac{\pi}{2}\cos\frac{\pi t}{2T}\right)\cos(\omega t)$$

After 2nd Polarizer:

(by destructive beating of the two replicas of the light)

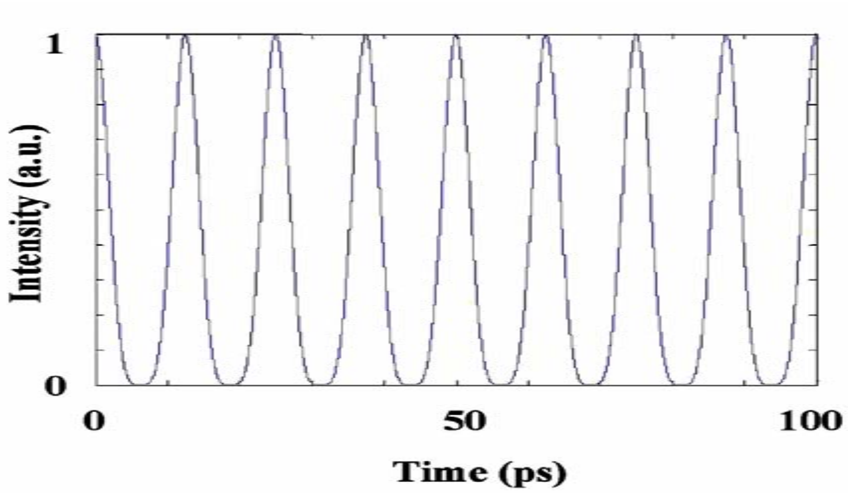
$$E_4 = \frac{E_{3a} - E_{3b}}{\sqrt{2}} = f(t) \propto A\left[\cos\left(\frac{\pi}{2}\sin\frac{\pi t}{2T}\right) - \cos\left(\frac{\pi}{2}\cos\frac{\pi t}{2T}\right)\right]\cos(\omega t)$$

$$f(t+T) = -f(t); \qquad f(NT + T/2) = 0$$

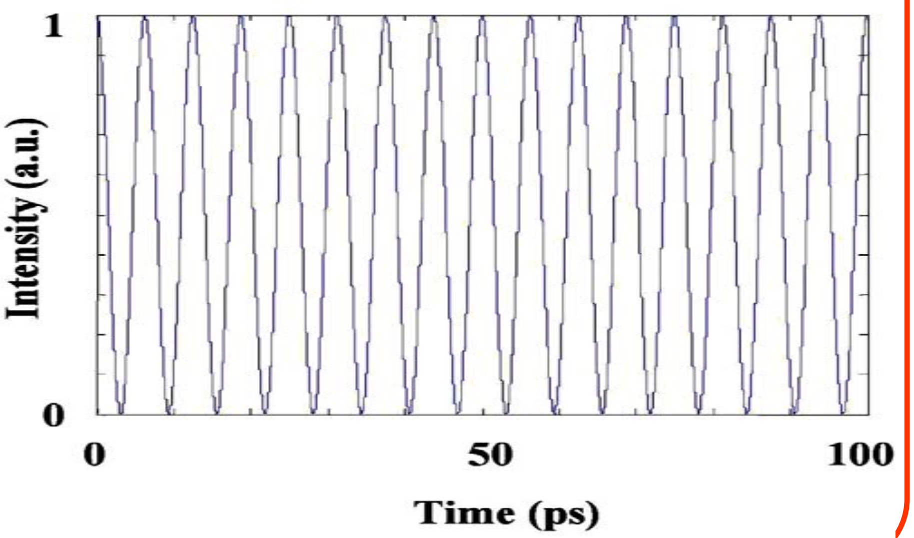
(f = 160 GHz chirp-free 50% CSRZ pulse train)

Simulation Results for Waveforms of Pulse Trains

80-GHz 33% RZ after the 1st Stage



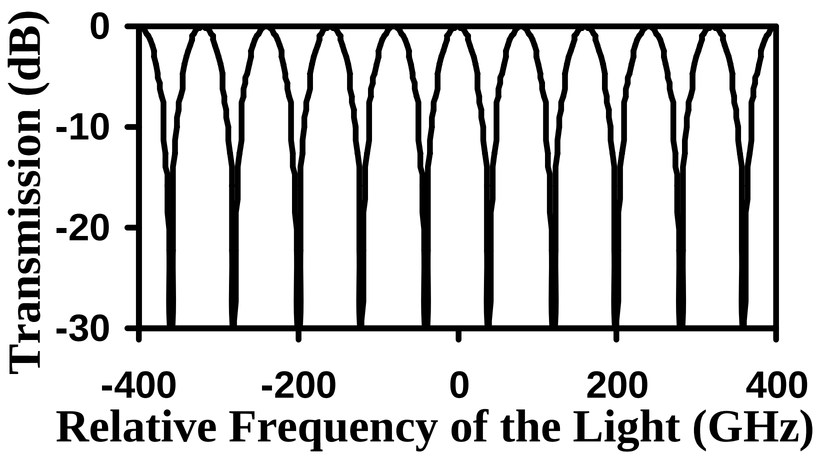
160-GHz 50% CS-RZ after the 2nd Stage



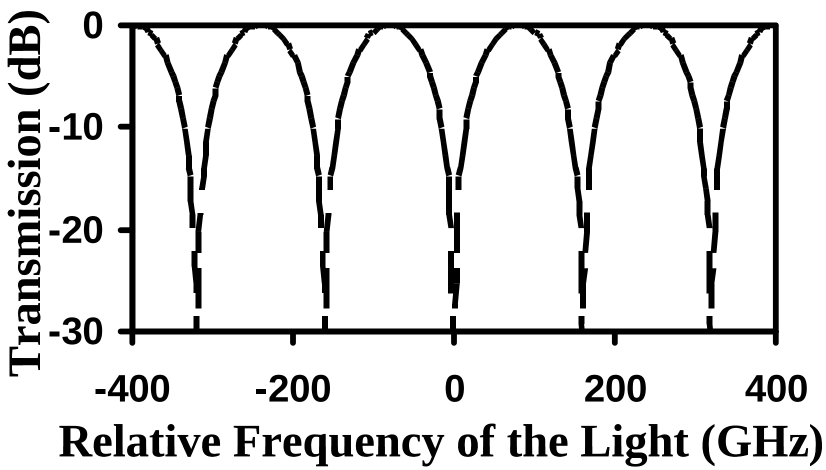
- **VPI Simulation shows that 80-GHz RZ and 160-GHz CSRZ are generated, which is consistent with calculation results.**

Transmission Spectra of the Interferometers (relative to 193.6 THz)

the First Stage

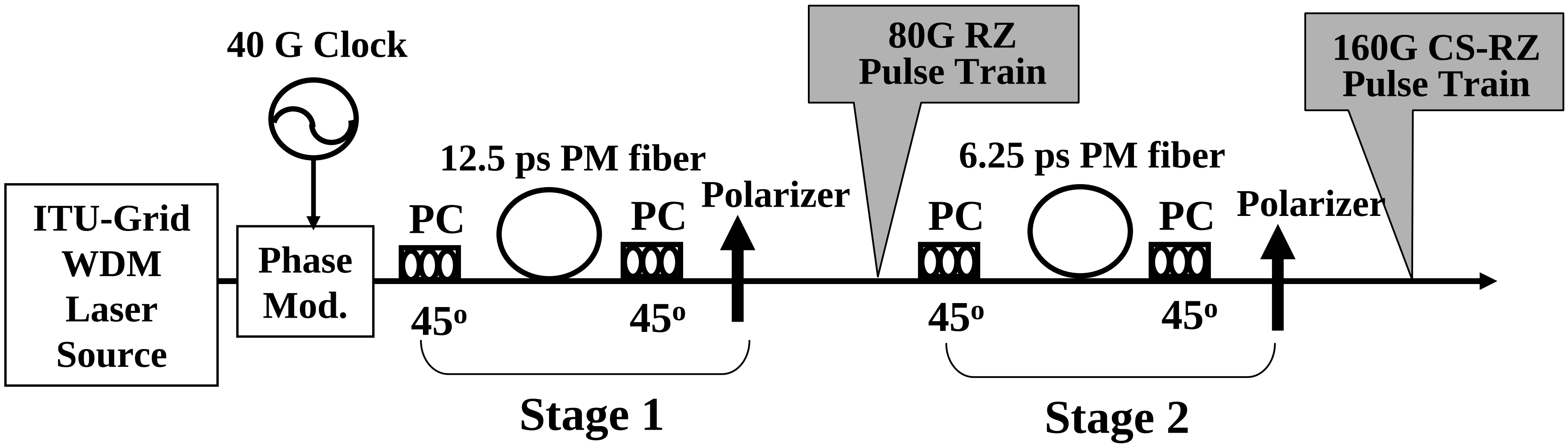


the Second Stage



- The 1st stage of the PM fiber with polarizer works as two-bit delay (*2T=12.5 ps*) interferometer with a FSR of *1/(2T)* (80 GHz).
- The 2nd stage works as one-bit delay (*T=6.25 ps*) interferometer with a FSR of *1/T* (160 GHz).
- Therefore, the channel spacing should be integral times of 160 GHz, which matches the 800-GHz-channel-spacing ITU-grid DWDM systems.

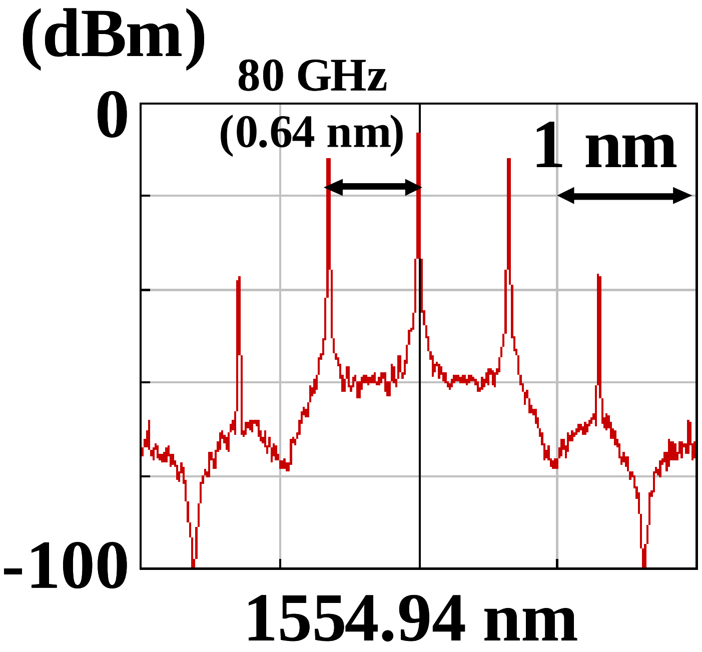
Experimental Setup of 160-GHz Pulse Generation Using Phase Modulator and PM fiber



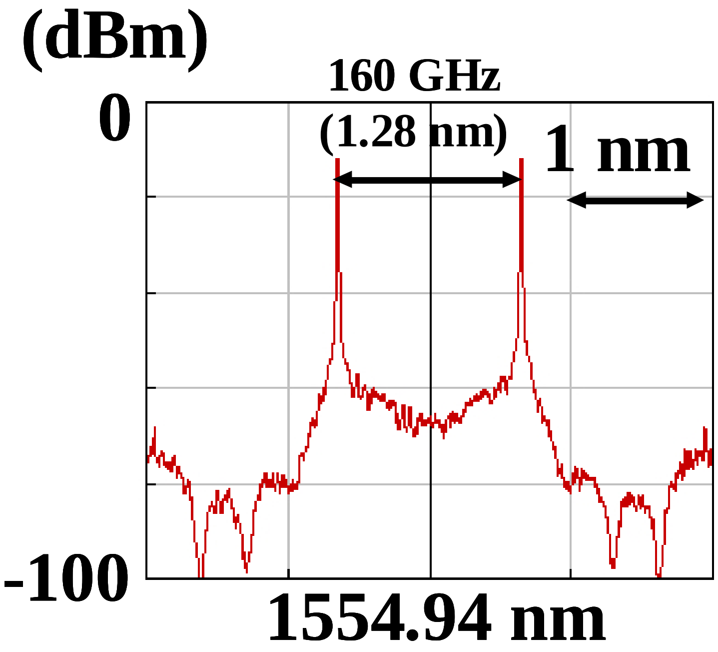
- PCs are used to align the light to be along the direction of 45° with respect to the PSPs or polarizer.
- All the PCs could be eliminated by 45° splicing the PM fiber.
- 4-channel ITU grid lights with a channel spacing of 800 GHz are launched into the system.

Simulation Results of Optical Spectra (Channel 192.8 THz)

80-GHz 33% RZ after the 1st Stage



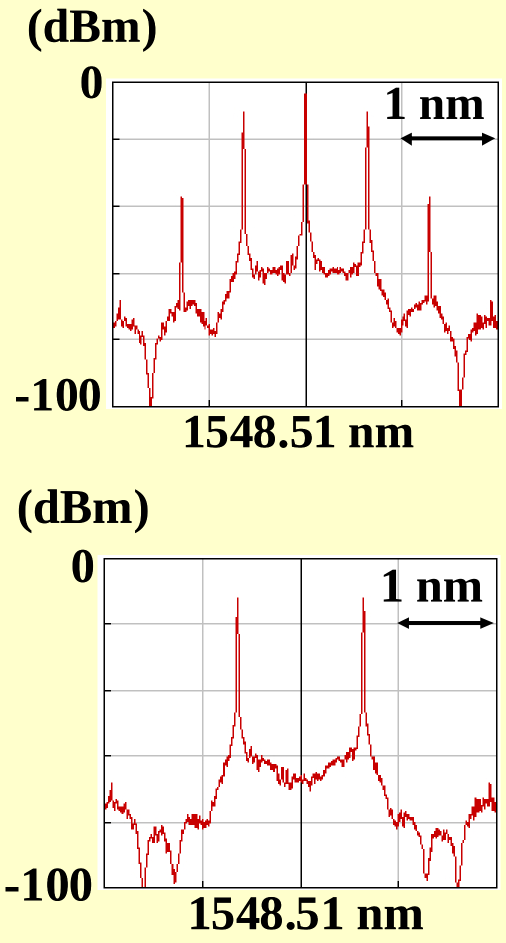
160-GHz 50% CSRZ after the 2nd Stage



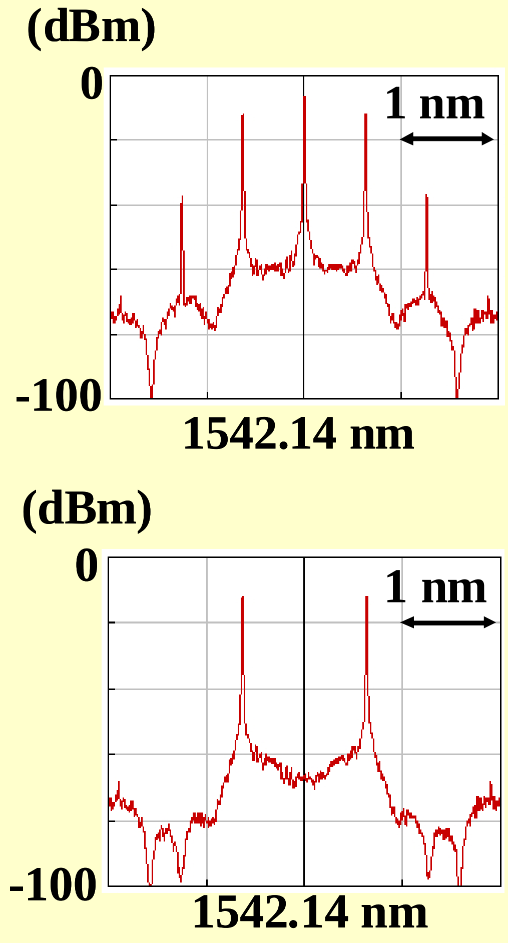
- After the 1st stage, the unwanted 40-GHz tones are filtered out.
- After the 2nd stage, the unwanted carrier and 80-GHz tones are filtered out.

Optical Spectra (The Other 3 Channels)

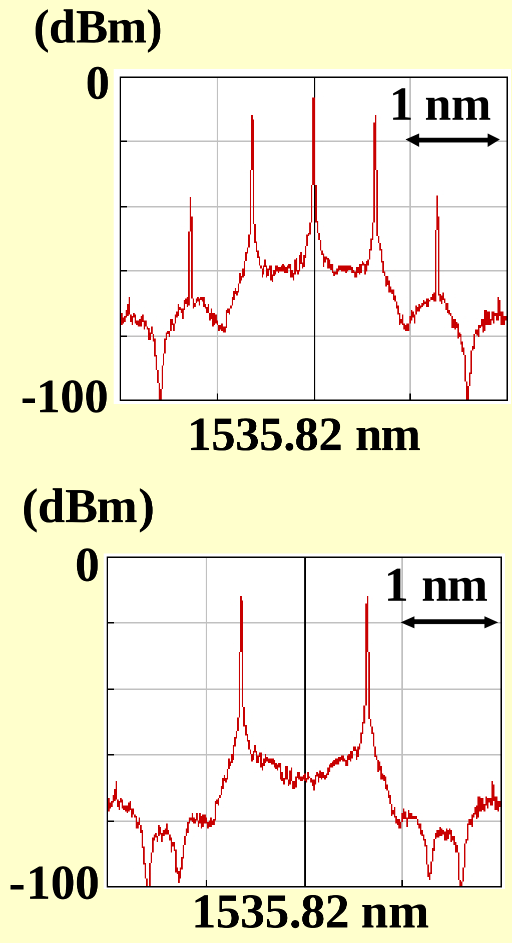
Channel 193.6 THz



Channel 194.4 THz



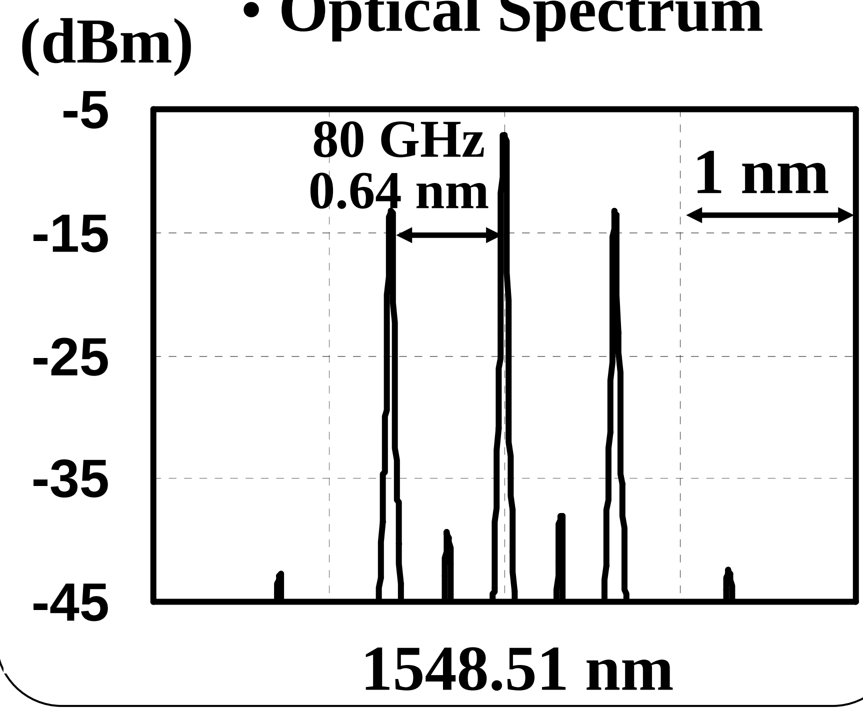
Channel 195.2 THz



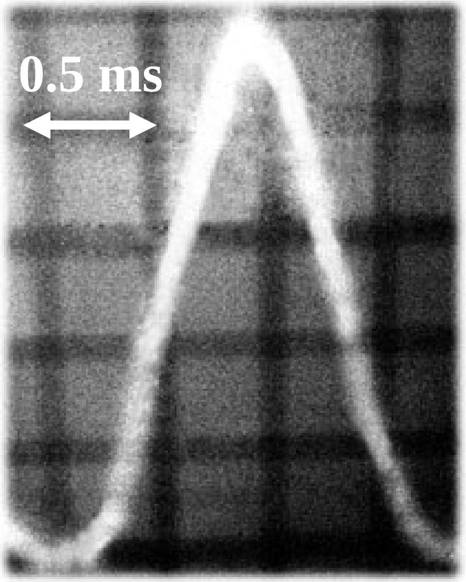
- The other 3 channels have the same results.
- The channel spacing is 800 GHz (5 times of 160 GHz).

1st Stage: 40-GHz Clock → 80-GHz RZ Pulse Train

- Optical Spectrum



- Autocorrelator Measurement

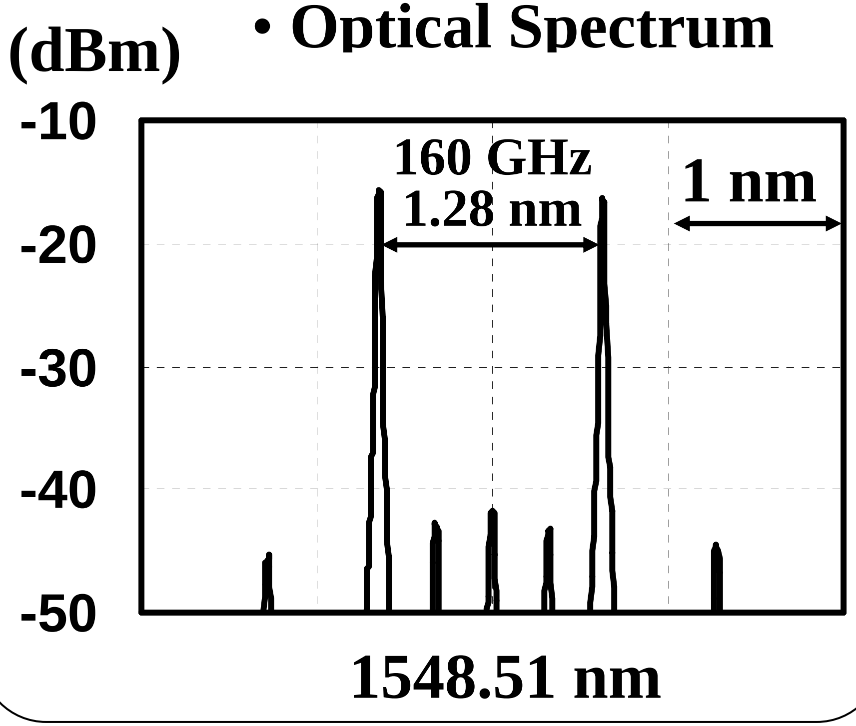


Scale Factor: 7.41 ps/ms

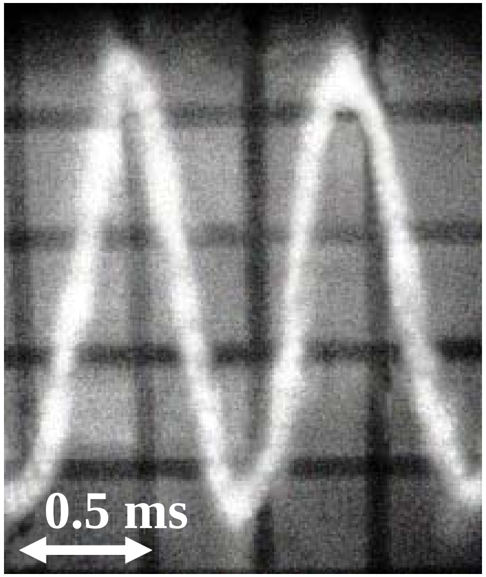
- The unwanted 40-GHz tone in the spectrum of the RZ pulse train is suppressed by about 30 dB.
- The measured pulse width: 0.8*7.41*0.74=4.4 ps, close to theoretical value of 4.16 ps.

2nd Stage: 80-GHz RZ Pulse Train → 160-GHz CSRZ Pulse Train

• Optical Spectrum



• Autocorrelator Measurement



Scale Factor: 7.41 ps/ms

- The unwanted lower tones (40 & 80 GHz) are suppressed by more than 25 dB.
- The measured pulse width: 0.45*7.41*1.0=3.3 ps, close to theoretical value of 3.12 ps.

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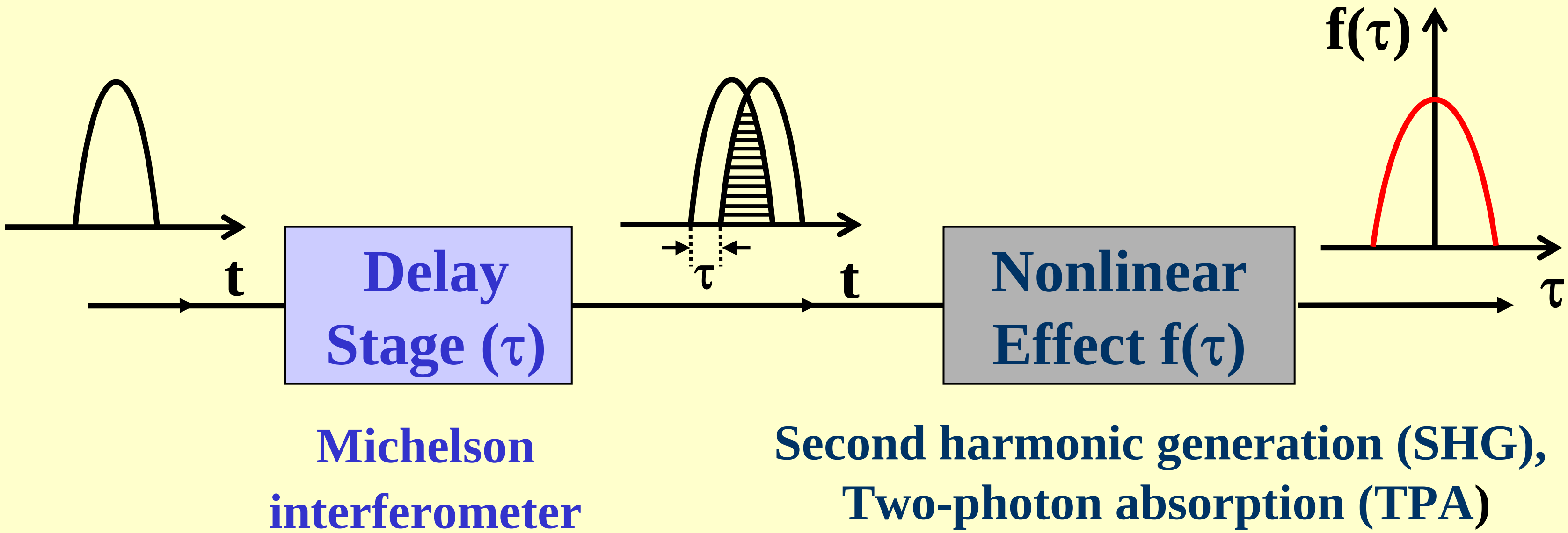
Autocorrelator for Measurement of Pulse Width

•Conventional Autocorrelator Concept

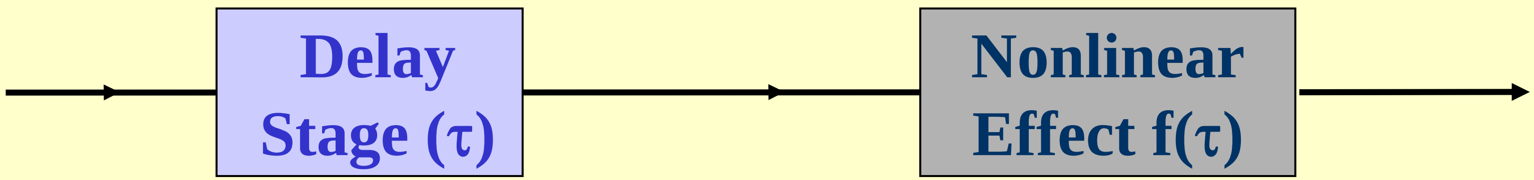


•Free space based, difficult alignment

- **All fiber based, wavelength independent, easy alignment are desirable for an autocorrelator.**

Previous All-Fiber Based Technique

OFC 2005

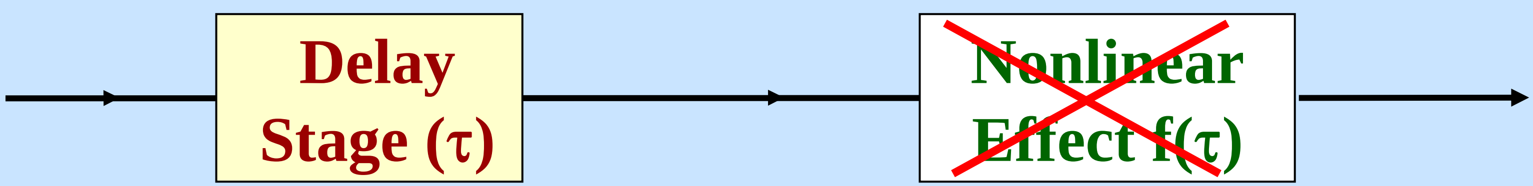


Tunable Differential-Group-Delay (DGD) Element

Polarimetric FWM in HNLF

•High optical power is required

New Technique



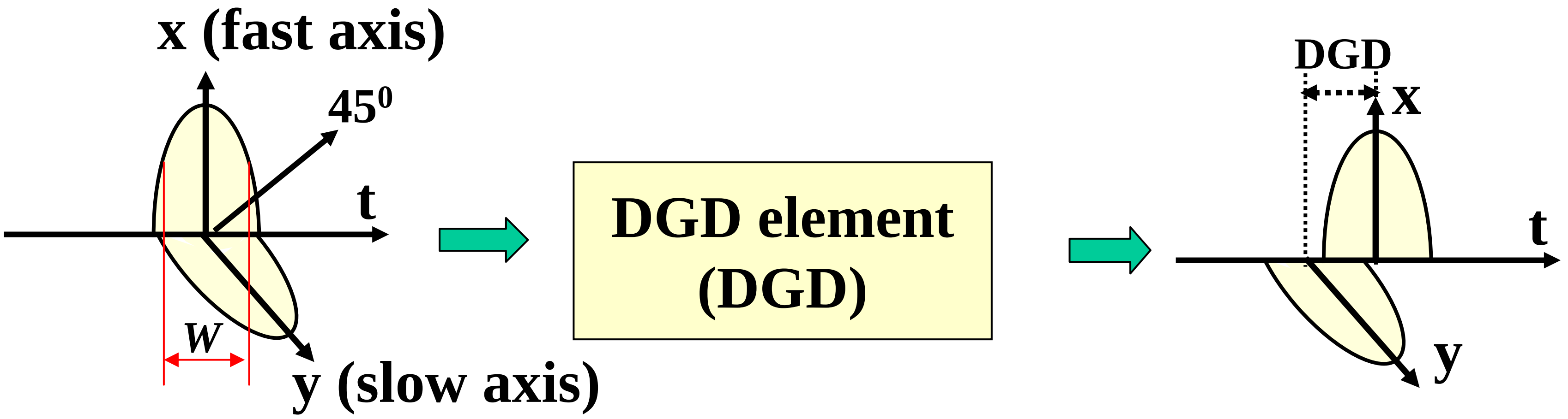
Tunable DGD Element

Pulse's Degree of Polarization (DOP)

•Much simpler, no high optical power is required

(*T. Luo et al., PTL 2006*)

DOP Dependence of DGD and Pulse Width



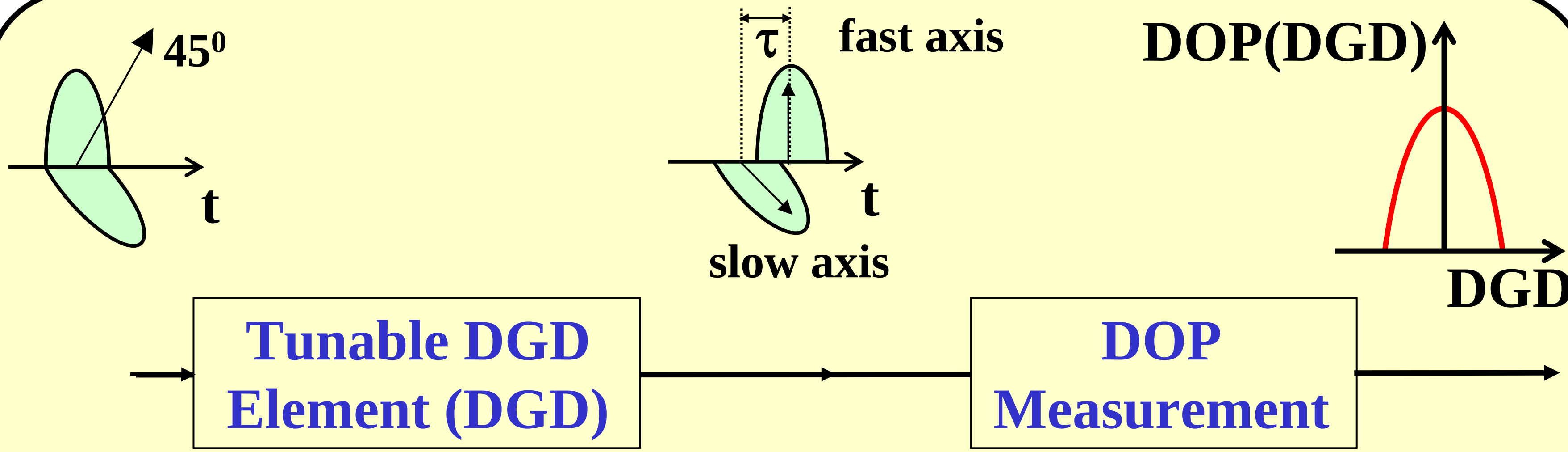
DOP = 1

0 < DOP (DGD, *W*) < 1

$$DOP\,(DGD) = \left| \frac{R_{in}(DGD) + R_{in}(-DGD)}{2R_{in}(0)} \right| = \left| \frac{R_{in}(DGD)}{R_{in}(0)} \right|$$

R_{in} is the autocorrelation function of the pulse

Autocorrelator Concept

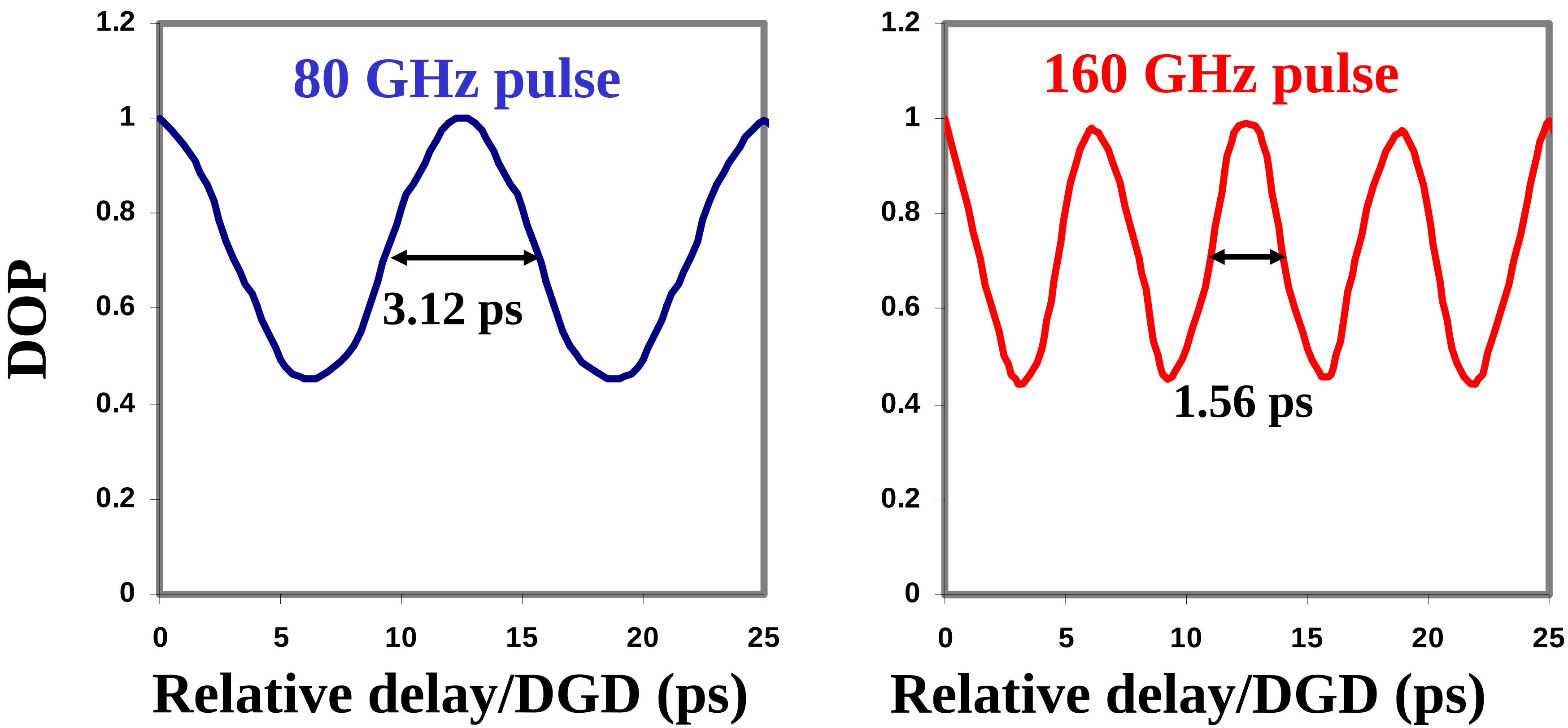


- **Delay stage:** the pulse is split into two polarization states and the two replica have a relative delay of DGD
- **DOP Measurement:** DOP depends on the shape of the incoming signal and DGD. The trace of DOP vs. DGD emulates the autocorrelation function of the pulse

$Pulse_{FWHM}$ = DOP $Trace_{FWHM}$*Scaling Factor

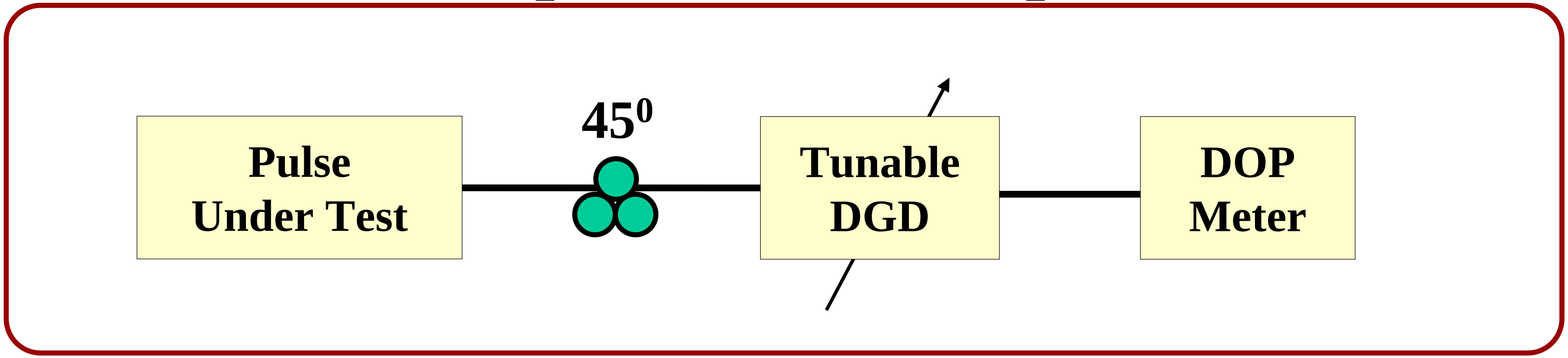
Simulation Results of DOP Measurement for Pulses

80 GHz and 160 GHz pulse trains



- DOP changes periodically with DGD.
- Full Width at Half Maximum (FWHM) of the DOP trace is proportional to the pulse width.

Experimental Setup



Pulses under test:

- **10, 20 and 40 GHz RZ Pulse Trains**
- **Mode-Lock Laser Pulse Train**

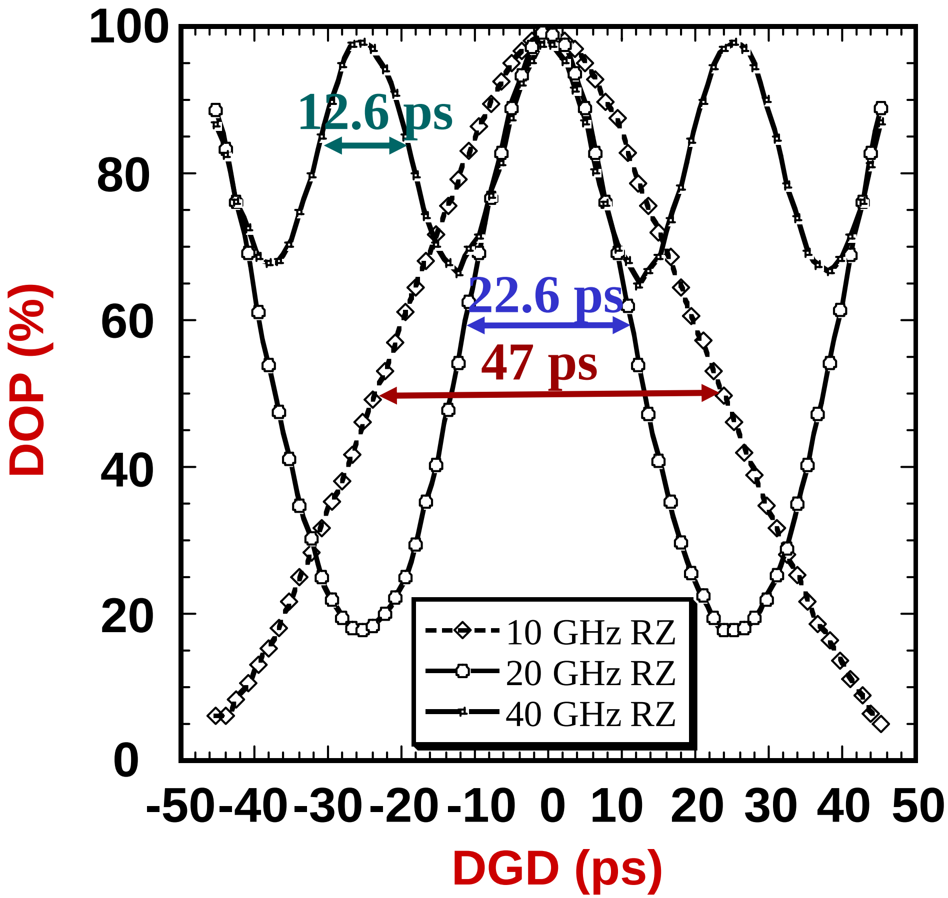
Optical power for DOP measurement:

-60 dBm – 0 dBm

Resolution of tunable DGD:

1.4 ps

Experimental Results –
RZ Pulse Scaling Factor Calibration



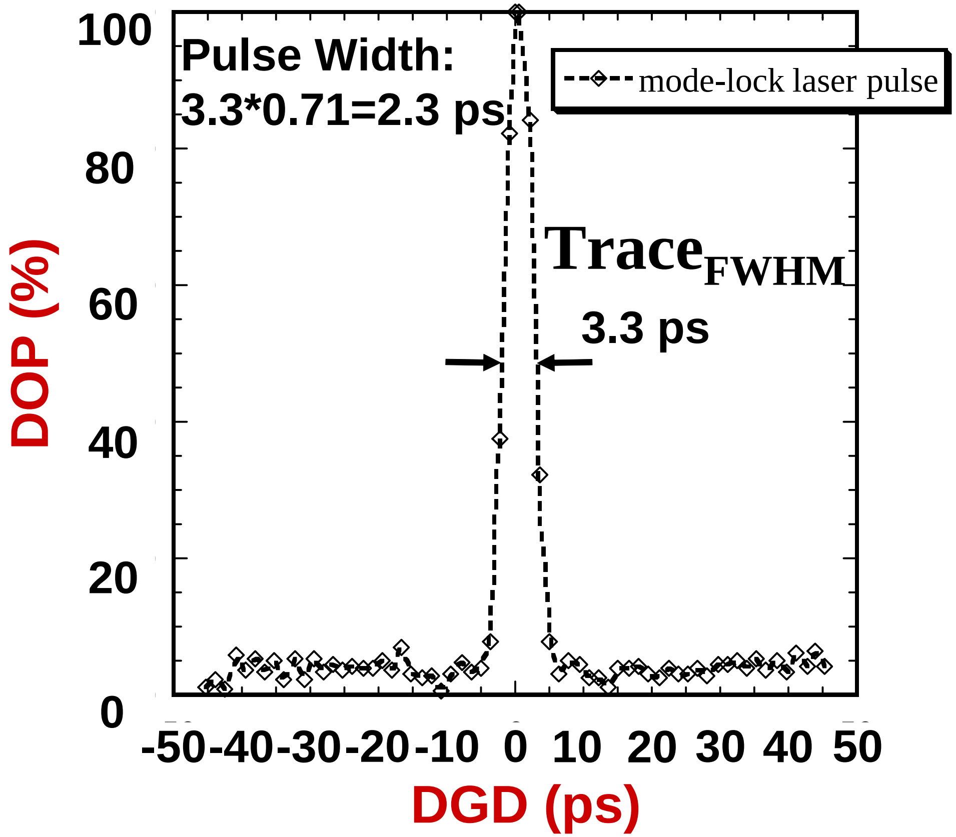
$\text{Trace}_{\text{FWHM}}$: 47, 22.6, 12.6 ps
Oscilloscope: 43, 23, 12.5 ps

Scaling factor = 1
$\text{Pulse}_{\text{FWHM}} = \text{Trace}_{\text{FWHM}} * 1$

- **The scaling factor of RZ pulses is 1.**
- **The measurement results are close to the results of oscilloscope.**

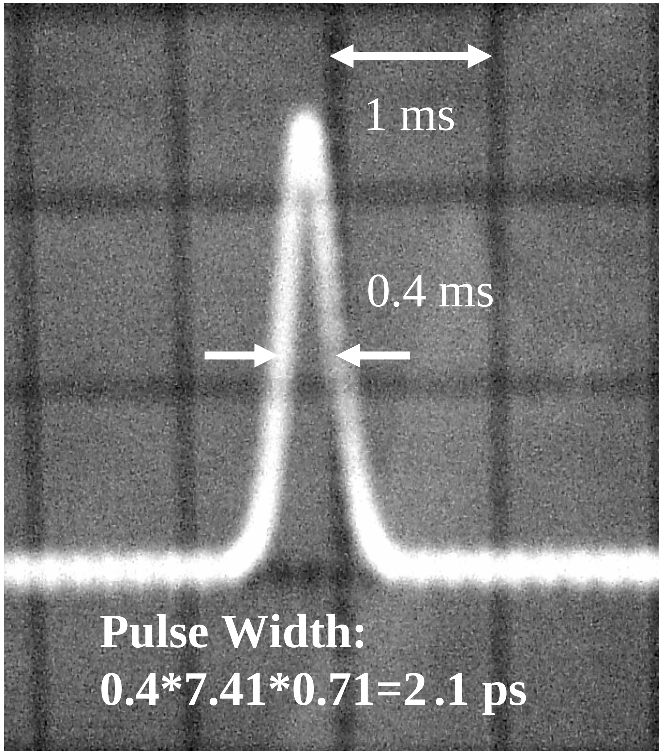
Experimental Result – Mode-Lock Laser Pulse

Our approach



Pulse Width: 3.3 * 0.71 = 2.3 ps

SHG approach



Pulse Width: 2.1 ps

Summary

- **We demonstrate a simple technique for ITU-grid multi-channel high-speed chirp-free optical pulse train generation:**
  - **After 20-GHz sinusoidal phase modulation, and filtered by PM fiber as one-bit delay interferometer, multi-channel 40-GHz RZ and CSRZ optical pulse trains are generated.**
  - **After 40-GHz sinusoidal phase modulation, and filtered by two-stages of PM fiber as interferometers, multi-channel 160-GHz chirp-free CSRZ optical pulse trains are generated.**
- **An autocorrelation technique is also demonstrated using a tunable DGD element and a DOP meter. This technique is all-fiber based, wavelength independent and requires less alignment, less optical power.**