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Discretely tunable Tm-doped fiber-based MOPA using FBG arrays as spectral filters

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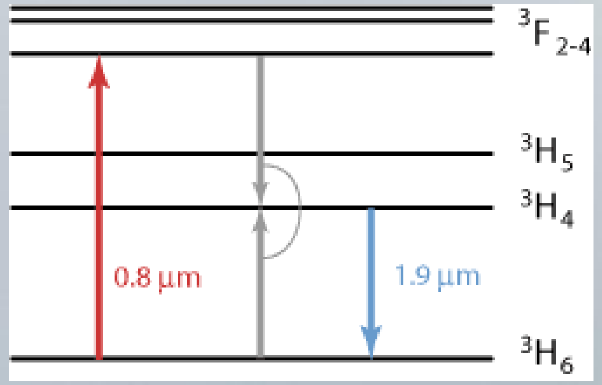
Outline

- Introduction
- Experimental setup of tunable PM Tm:MOPA
- Characterization of seed and amplifier performance
- Influence of non-PM filter design
- Summary

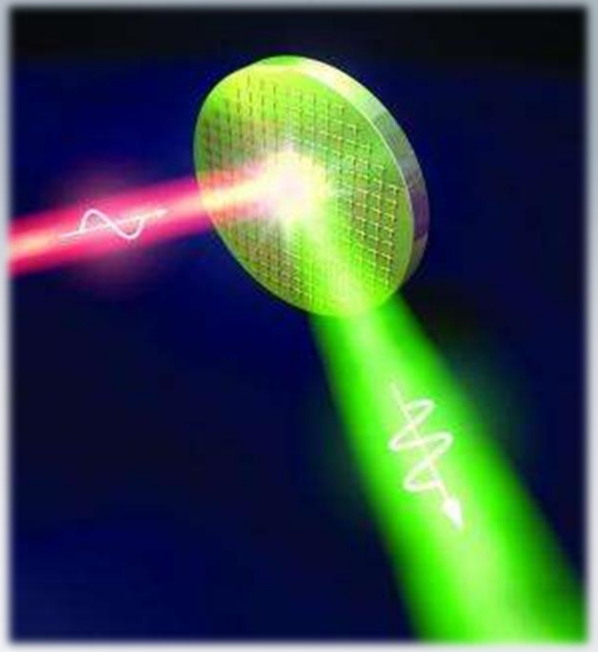
Motivation

- **Tm fiber lasers @ 2µm**
  - Large gain region: 1800nm-2100nm
  - Efficient pumping @793nm due to cross relaxation
  - Enhanced nonlinear thresholds



[RP Photonics]

- **Applications**
  - Biophotonics and spectroscopy
  - Material processing (e.g. polymers)
  - Nonlinear frequency conversion to MIR or THz



[Cockrell School of Engineering, University of Texas]

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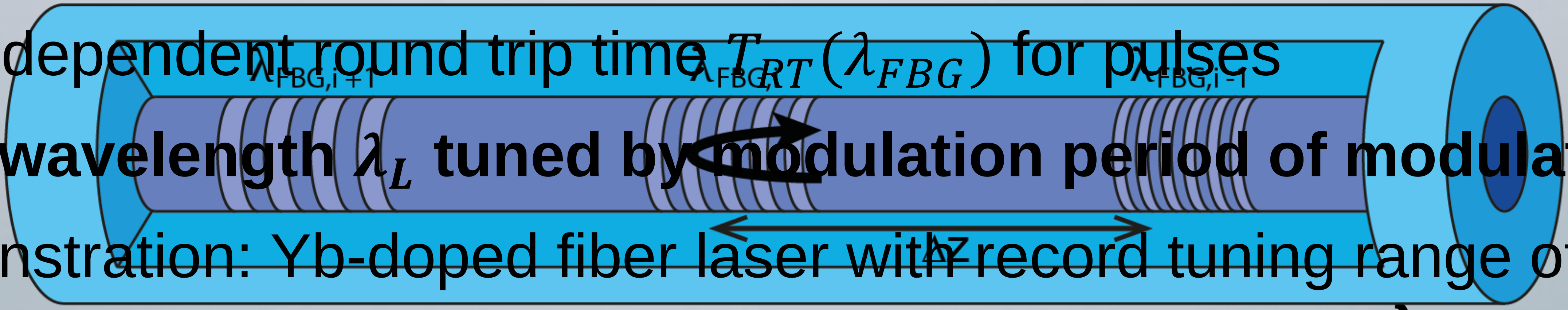
Discrete dispersion tuning

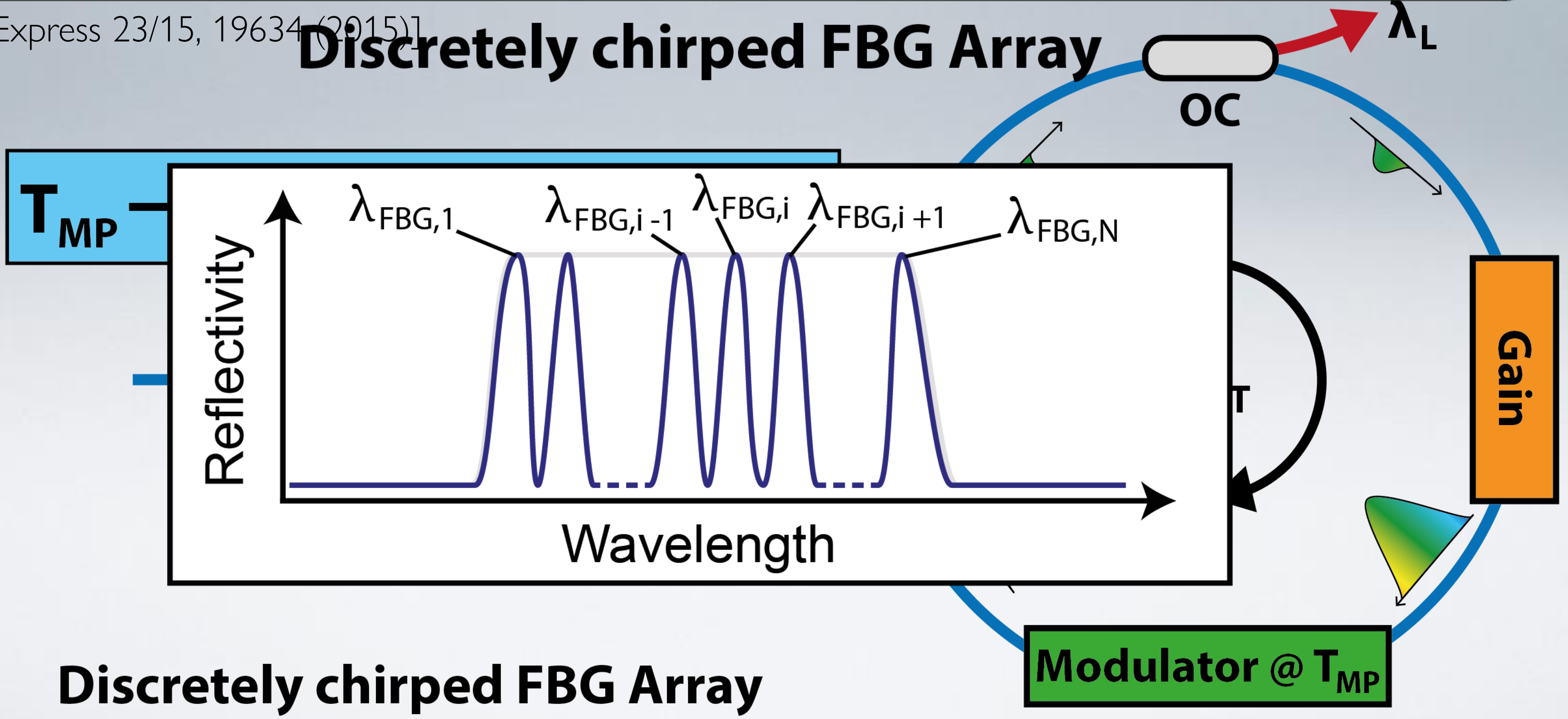
- Ring resonator configuration with **discretely chirped FBG array**

⇨ spectrally dependent round trip time $T_{RT}(\lambda_{FBG})$ for pulses

- **Emission wavelength λ_L tuned by modulation period of modulator** $T_{MP} = T_{RT}$
- First demonstration: Yb-doped fiber laser with record tuning range of 74nm

[Tiess, T., et al., Optics Express 23/15, 19634 (2015)]





Discretely chirped FBG Array

Targets of this work

- Investigate tuning principle at 2µm using Tm:doped fiber lasers
- Realize PM layout for linear polarized light
  - Influence of PM and non-PM filter layout
- Boost Power level in MOPA configuration

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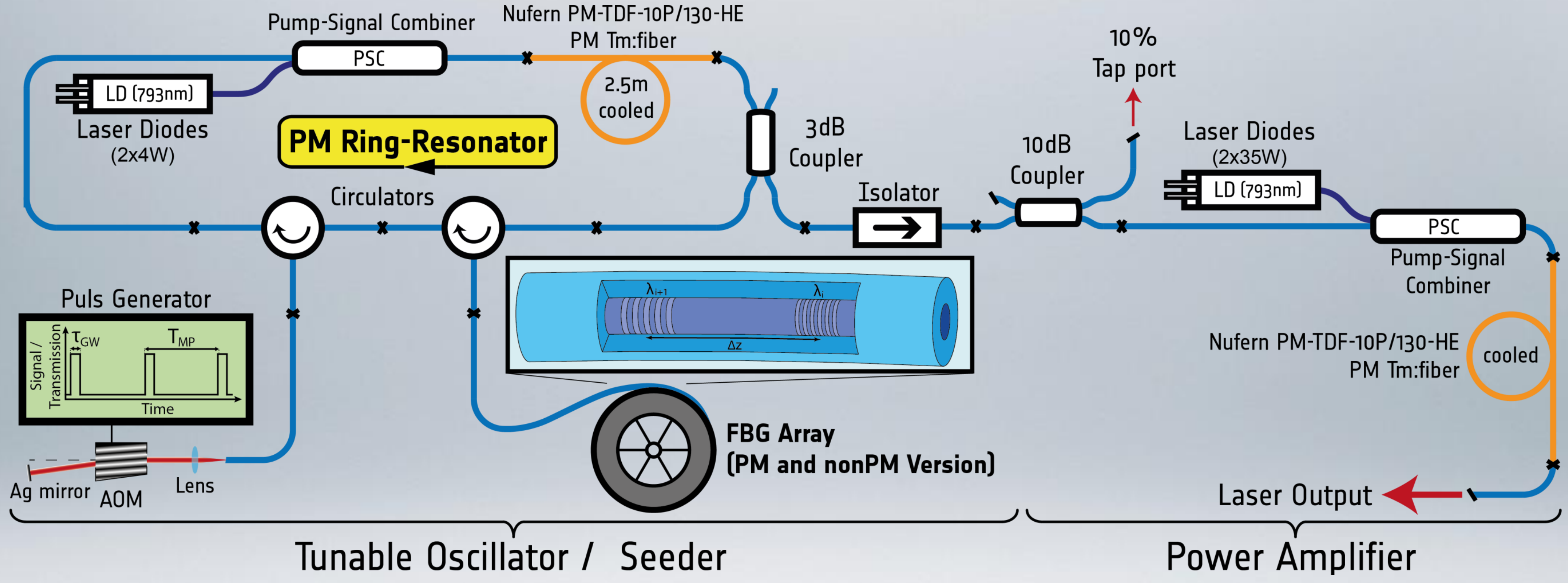
Experimental Setup



- **M**aster **O**scillator **P**ower **A**mplifier (MOPA) to boost the power level
- Fast-axis blocked PM circulators ensure linear polarization
- Free-space coupled AOM in retro-reflective setup (rise-time ~60ns)

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Spectral filters

- HR FBG Array inscribed in commercial PM fiber used in most experiments

Spectral filters	PM FBG Array	nonPM FBG Array
Inscription technique	Multiple shot with fs-UV-Laser	Single-shot during fiber drawing
Fiber	PM1550 (commercial)	Photosensitive, nonPM (in house)
Reflectivity R	**R>99%**	**R ≈ 10-20%**
Wavelength range	1920nm – 1980nm	1900nm – 2100nm
Number of FBGs	5	100
Linewidth of FBG $\Delta\lambda_{FBG}$	$\Delta\lambda_{FBG} \approx$ **1.4nm**	$\Delta\lambda_{FBG} \approx$ **120pm**

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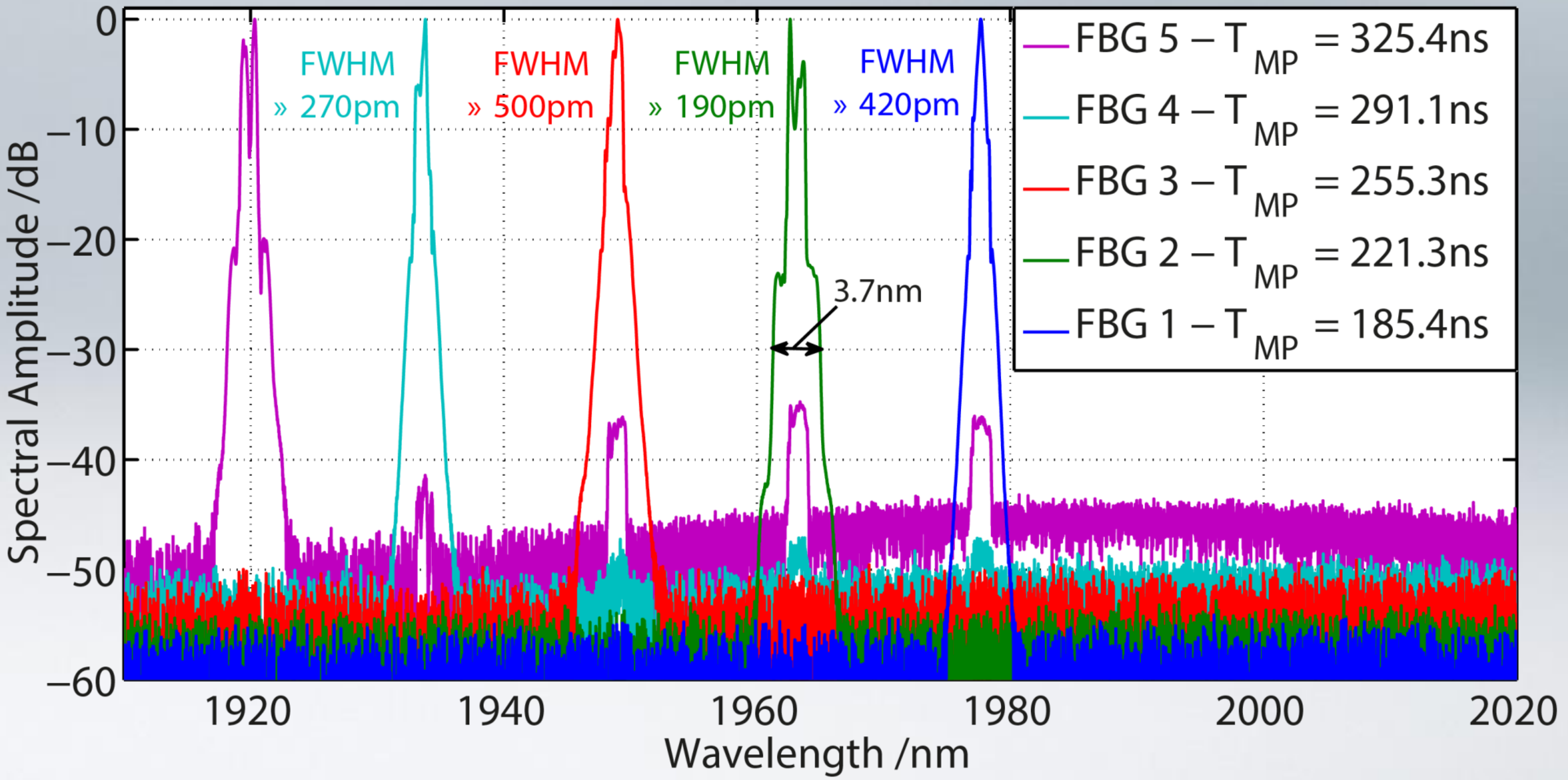
Emission properties of Seeder

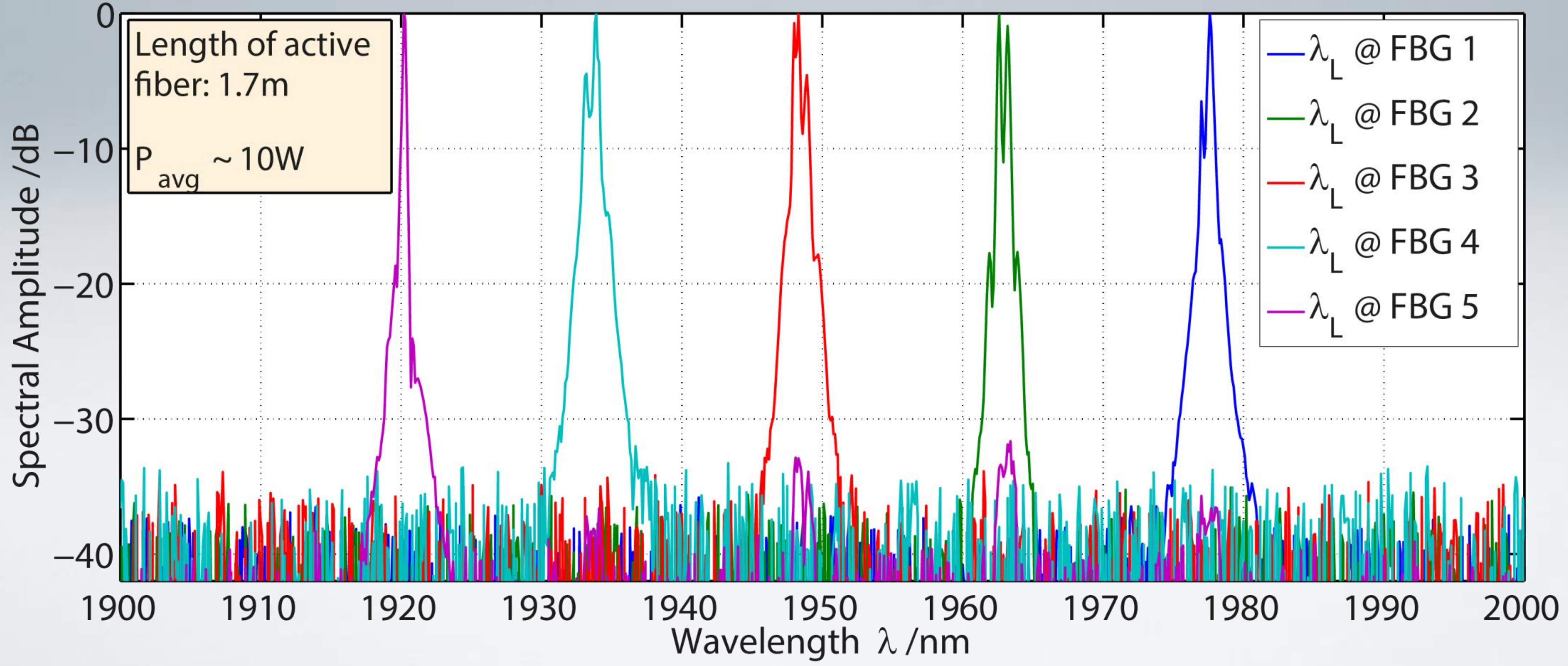
- Power characteristics: P_{avg} ~600mW & P_{peak} ~10W & E_{pulse} ~0.15µJ
- Pulse duration: 10-20ns
- Spectrum:
  - Very good spectral contrast (mostly >50dB)
  - Parasitic feedback peaks at FBG5
  - Broad HR FBG responses result in split up emission peaks (random)



Emission Spectra of Amplifier

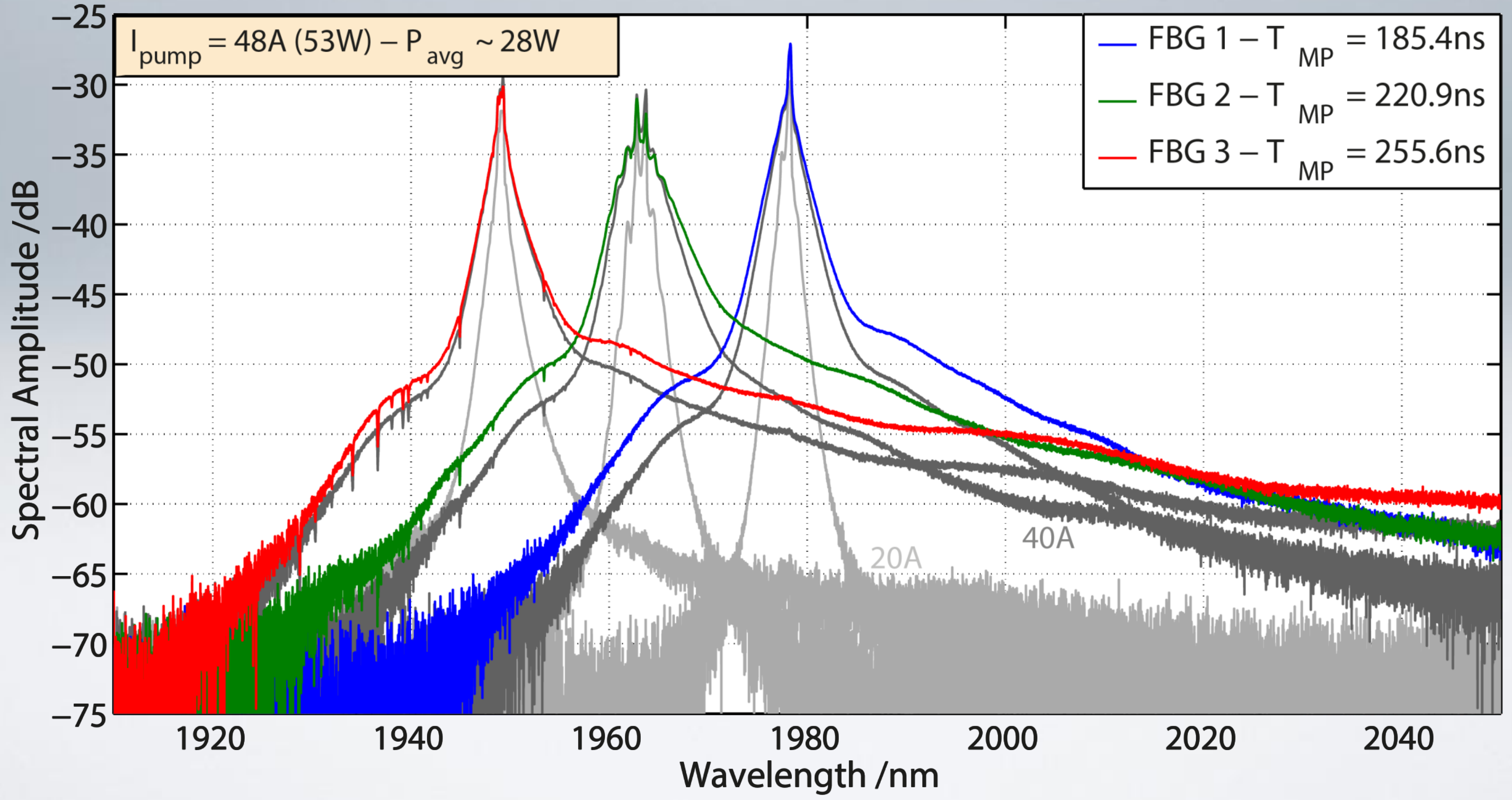
- **Active fiber (AF) length: 1.7m**
- Power scaled to >10W average power with a slope of 48%
- Further power scaling prohibited by thermal issues due to residual pump power (~70% absorbed)

  ⇨ **change AF length to 5m**



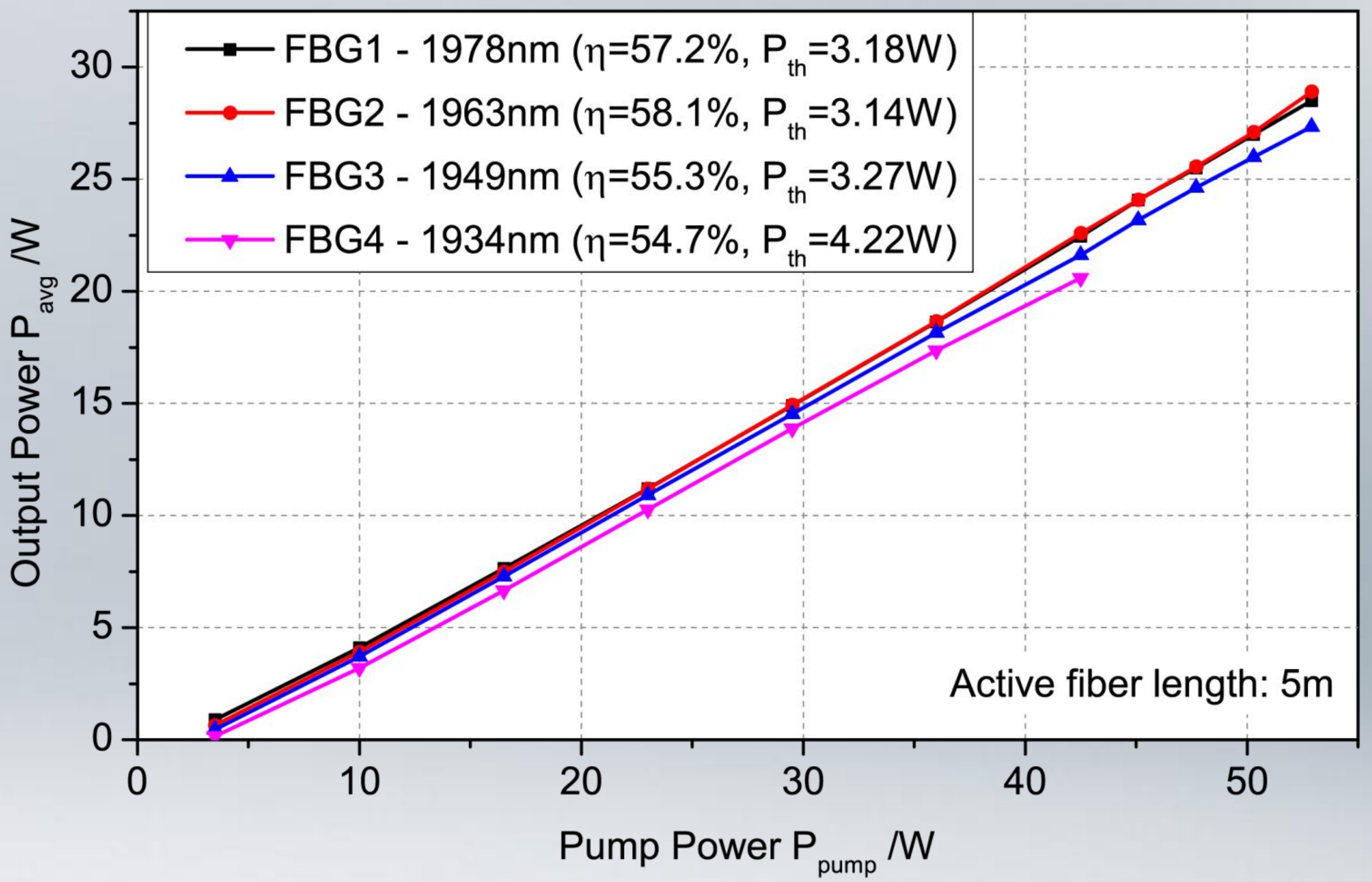
Emission Spectra of Amplifier

- Amplifier gain spectrum does not cover all emission wavelengths
- Linewidth (FWHM) does not change
- Nonlinear spectral broadening at peak tails



Power characteristics and PER

- Amplification of seed signal by ~17dB
- **P_{avg} ~28W & E_{pulse} ~6µJ**
- Power limitation due to thermal management of active fiber
- Excellent slope of up to 58%
- **PER>17dB**



Pump @ 8.7W	Power (p-pol)	Power (s-pol)	PER
1978nm (FBG1)	2.84W	14.6mW	**22.9dB**
1934nm (FBG4)	2.03W	35mW	**17.6dB**

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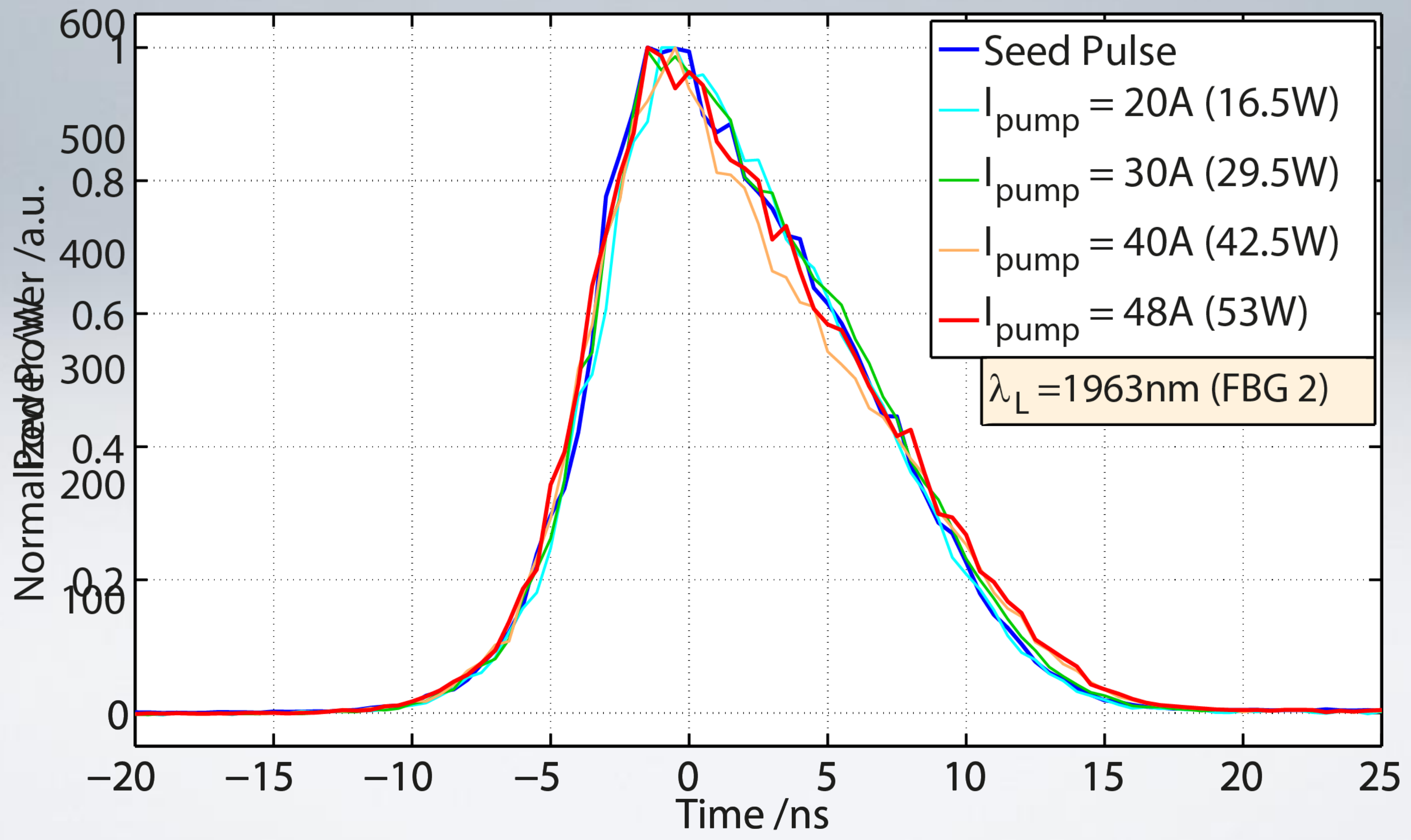
Pulse properties

- τ_{pulse} ≅ **11ns** (asymmetric shape)
- P_{peak} of more than 550W → Amplification ~ 17dB
- Pulse shape independent of power level



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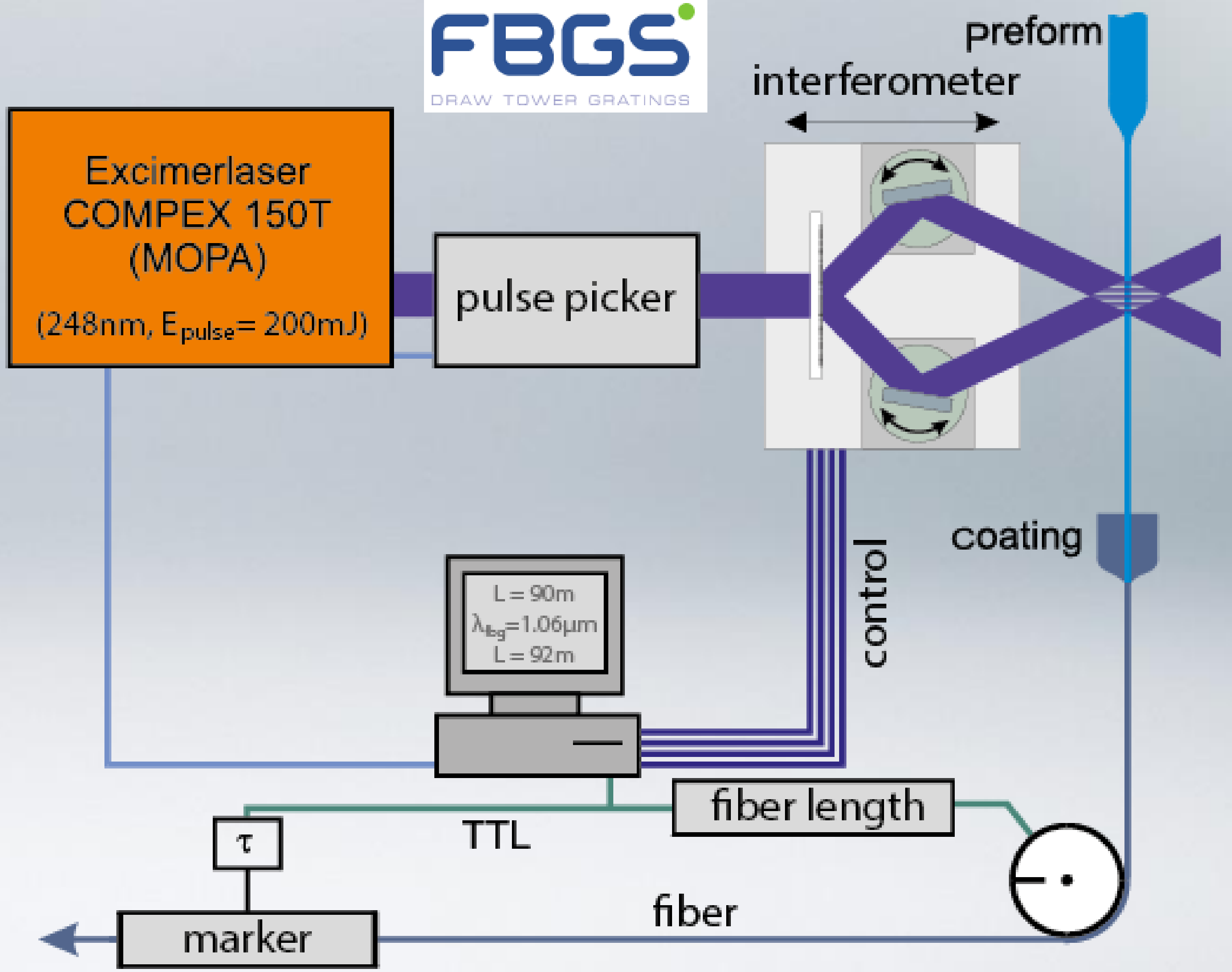
Draw Tower Gratings: FBG arrays

- Highly productive inscription during fiber drawing process
- Single-shot illumination!
  ⇨Reflectivity ≤ 40%
- Feedback wavelength tunable during inscription via interferometric setup
- Commercialized through FBGS Technologies GmbH



[V. Hagemann, *Dissertation*, FSU Jena (2000)]

Non PM Filter layout

- Second inscription technique: draw-tower inscription of FBG
  - Enables large FBG arrays (many gratings) with narrow linewidth
  - Restricted to photosensitive and non-PM fibers
- Commercialized through FBGS Technologies GmbH in Jena/Germany

[Chojetzki, C., et al., et al., Opt. Eng. 44(6): 060503, (2005)]

Spectral filters	PM FBG Array	nonPM FBG Array
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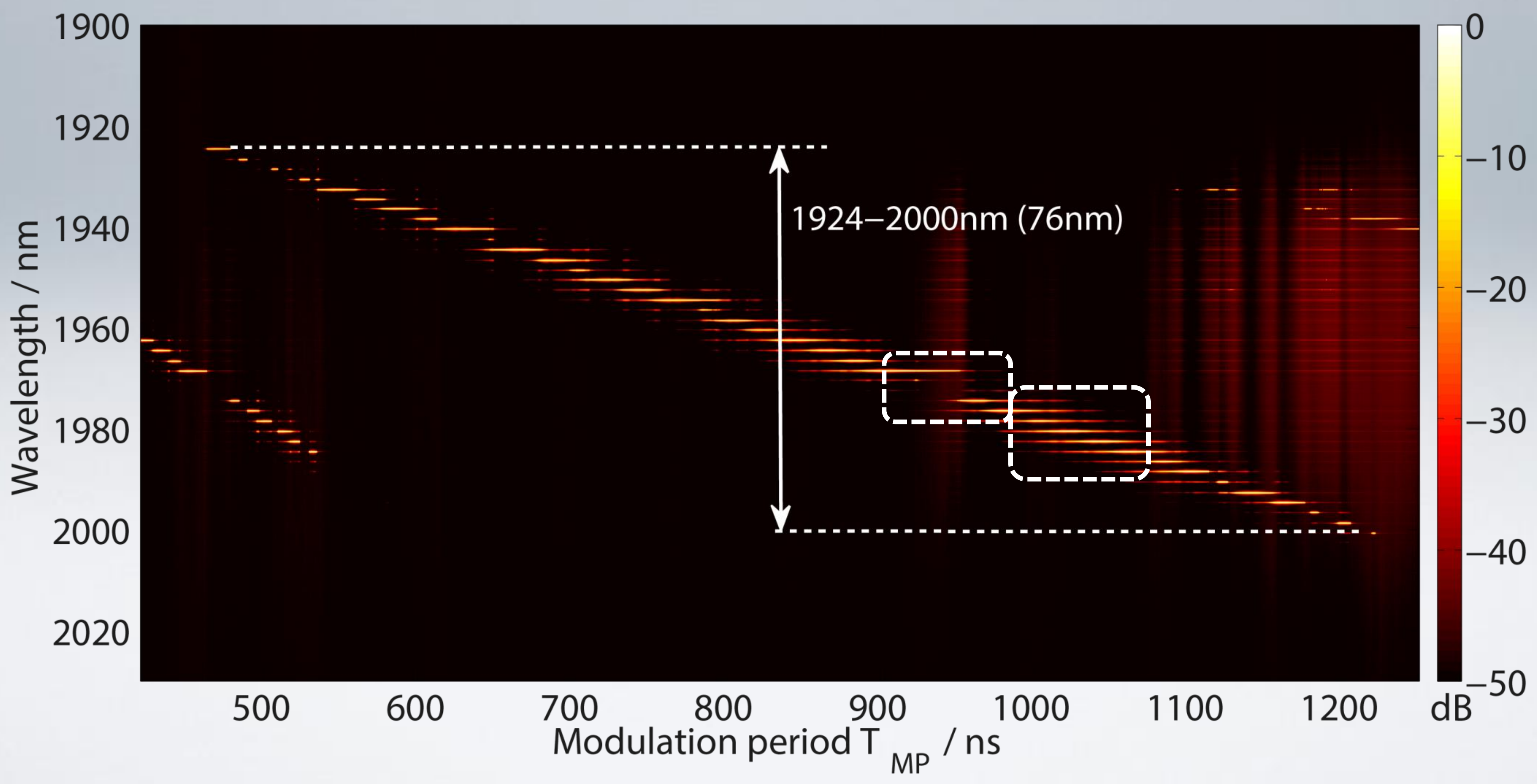
Fiber	PM1550 (commercial)	Photosensitive, nonPM (in house)
Reflectivity R	**R>99%**	**R ≈ 10-20%**
Wavelength range	1920nm – 1980nm	1900nm – 2100nm
Number of FBGs	5	100
Linewidth of FBG $\Delta\lambda_{FBG}$	$\boldsymbol{\Delta\lambda_{FBG}}$ **≈ 1.4nm**	$\boldsymbol{\Delta\lambda_{FBG}}$ **≈ 120pm**

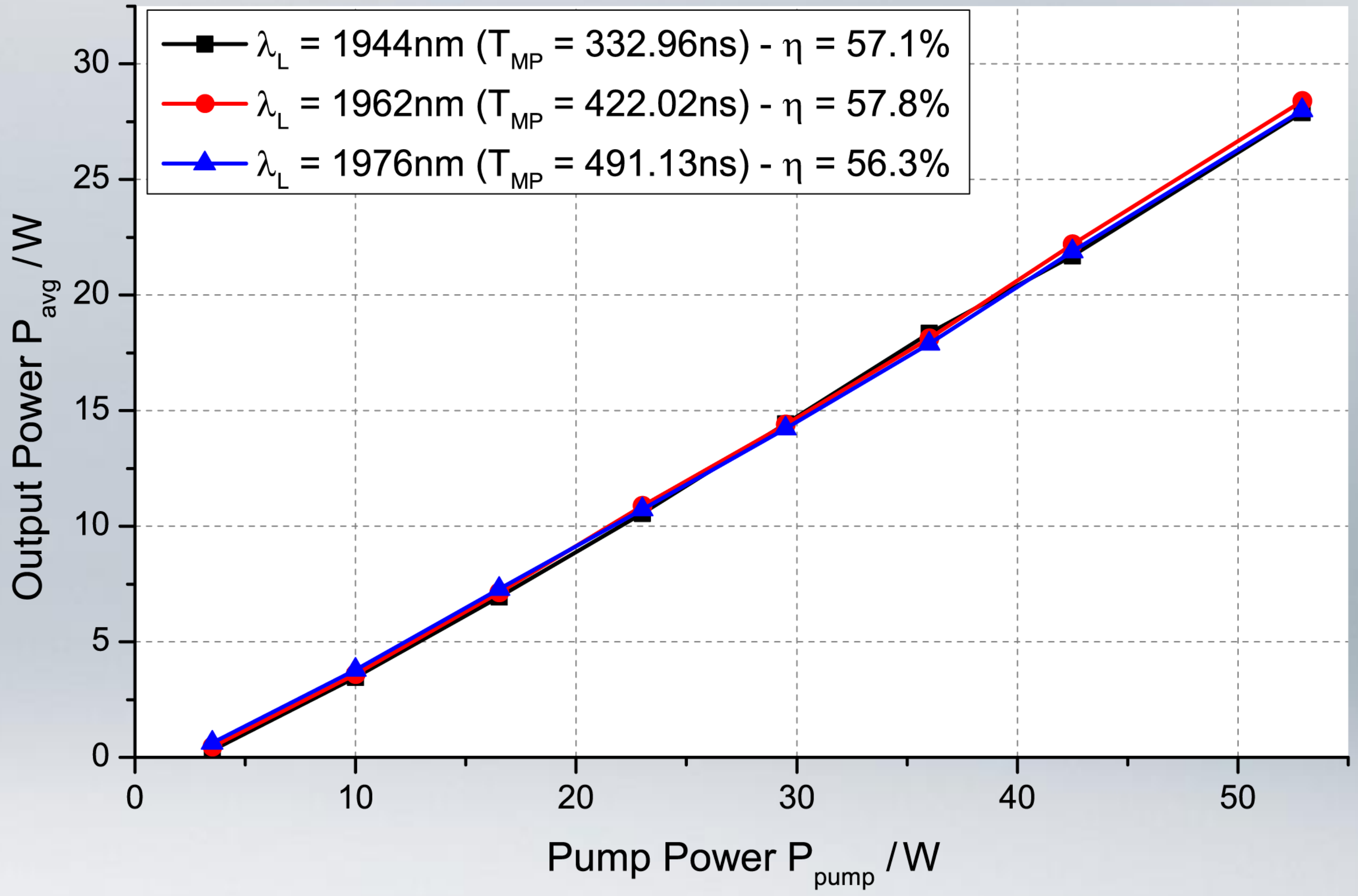
Tuning behavior seeder

- Tuning range of 76nm with narrow linewidth and very good contrast
- Coupling / multiple emission lines (→ slow rise time of AOM)
- Some emission lines not covered (→ polarization mixing in filter)



Power characteristics and PER

- Similar power characteristics of amplifier as with HR FBG Array
- Larger Seeder threshold (~30% @ 1976nm)
- Slope of amplifier >55%
- PER >20dB (spectrally resolved PER ~27dB) → **no PM Filter layout required**



Pump @ 23W	Power (p-pol)	Power (s-pol)	PER
1976nm	8.93W	48mW	**22.7dB**
1962nm	8.9W	76mW	**20.7dB**
1944nm	8.9W	87mW	**20.1dB**

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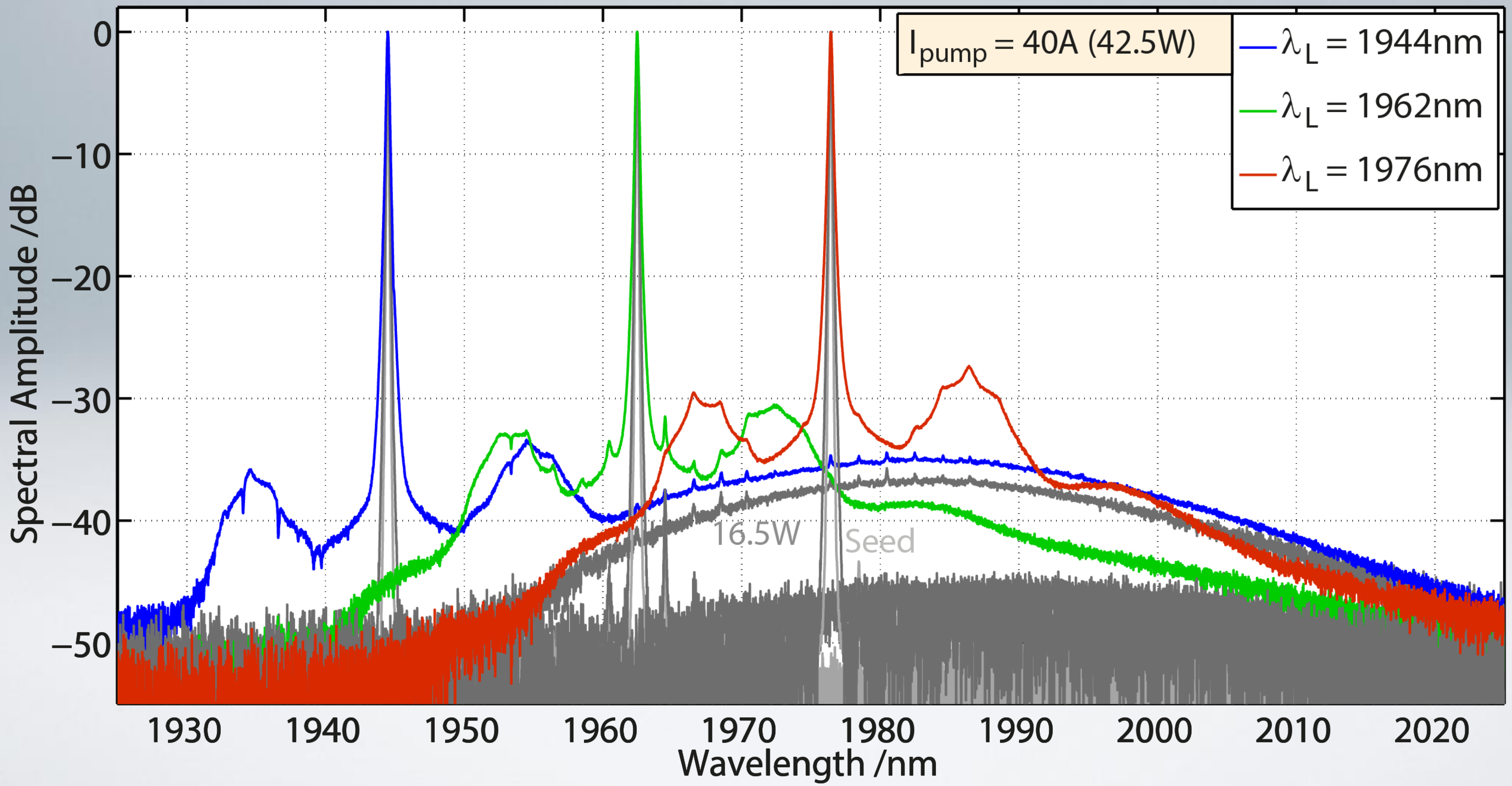
Emission Spectra of Amplifier

- Narrow linewidth, high signal contrast, stable peak wavelength
- With increasing power: **nonlinear broadening due to FWM**



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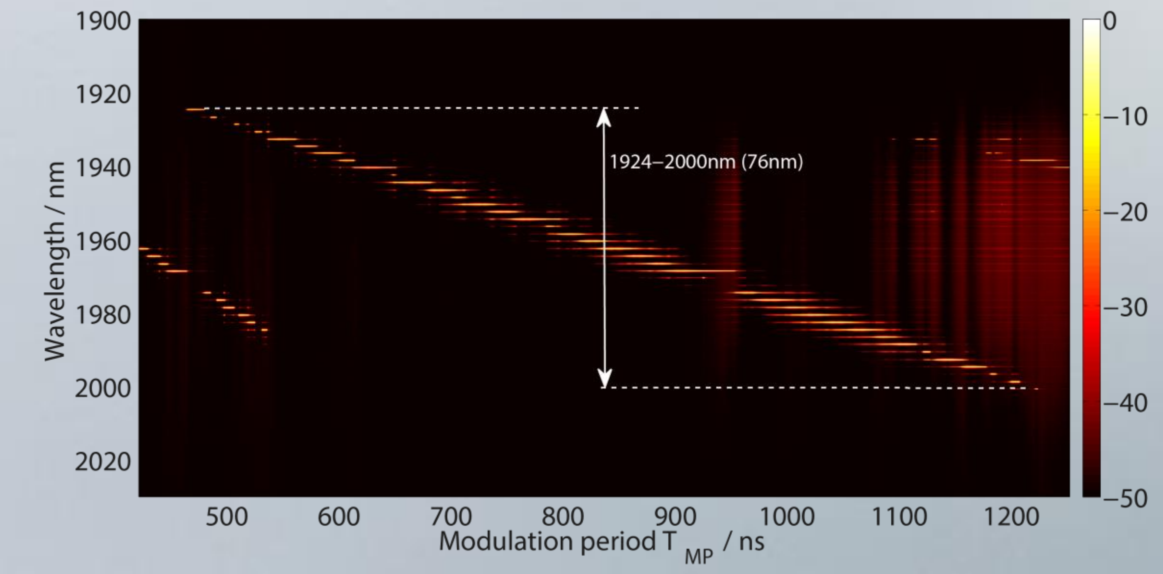
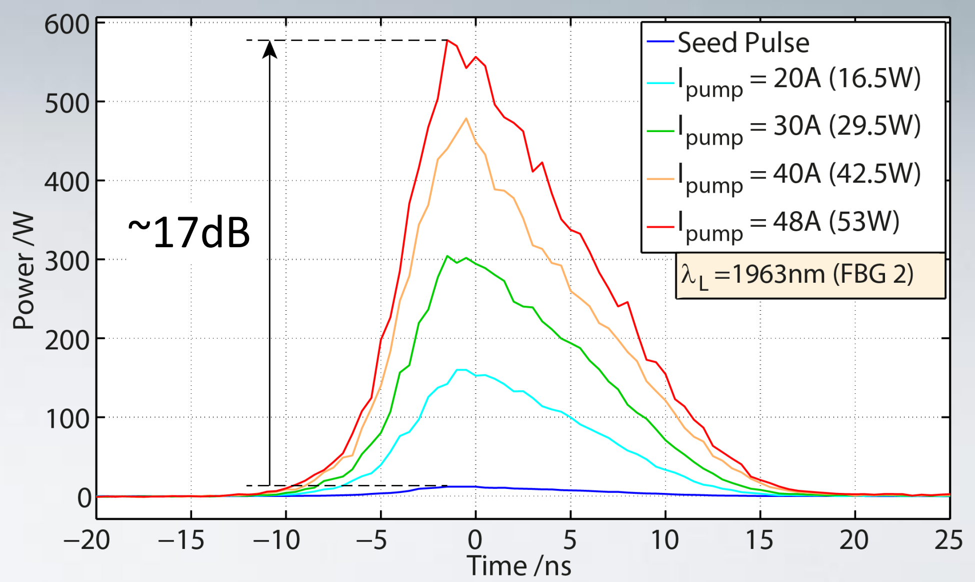
Summary

- Tuning range of 76nm with PM Tm MOPA
- Power scaled to P_{peak}>500W, P_{avg}>28W
- PER~20dB
- Also non-PM filter design suitable
- With optimized fiber design and length, higher peak power and larger tuning range possible





THANK YOU FOR YOUR ATTENTION

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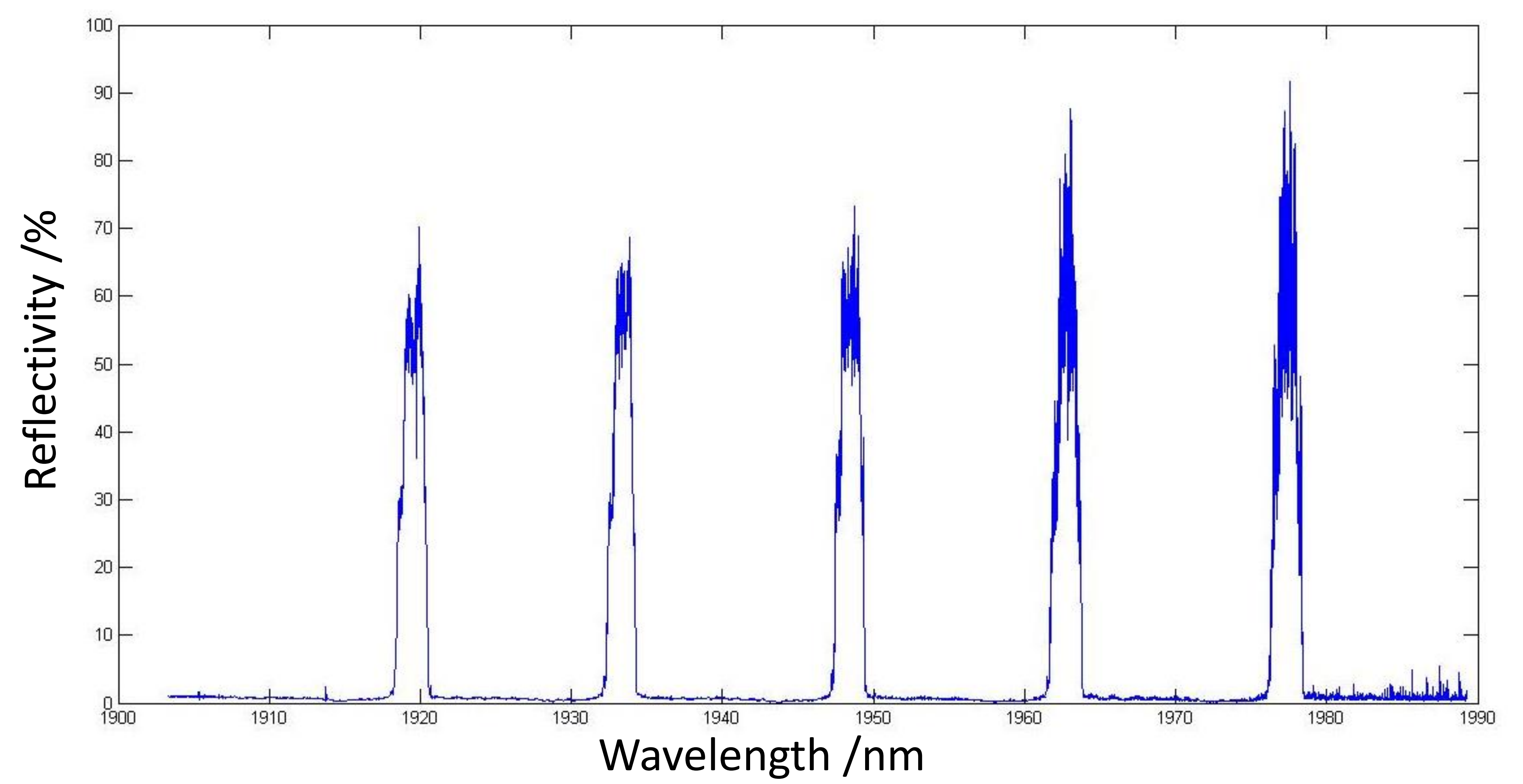
Contact: matthias.jaeger@leibniz-ipht.de

Advantages of tuning via FBG array

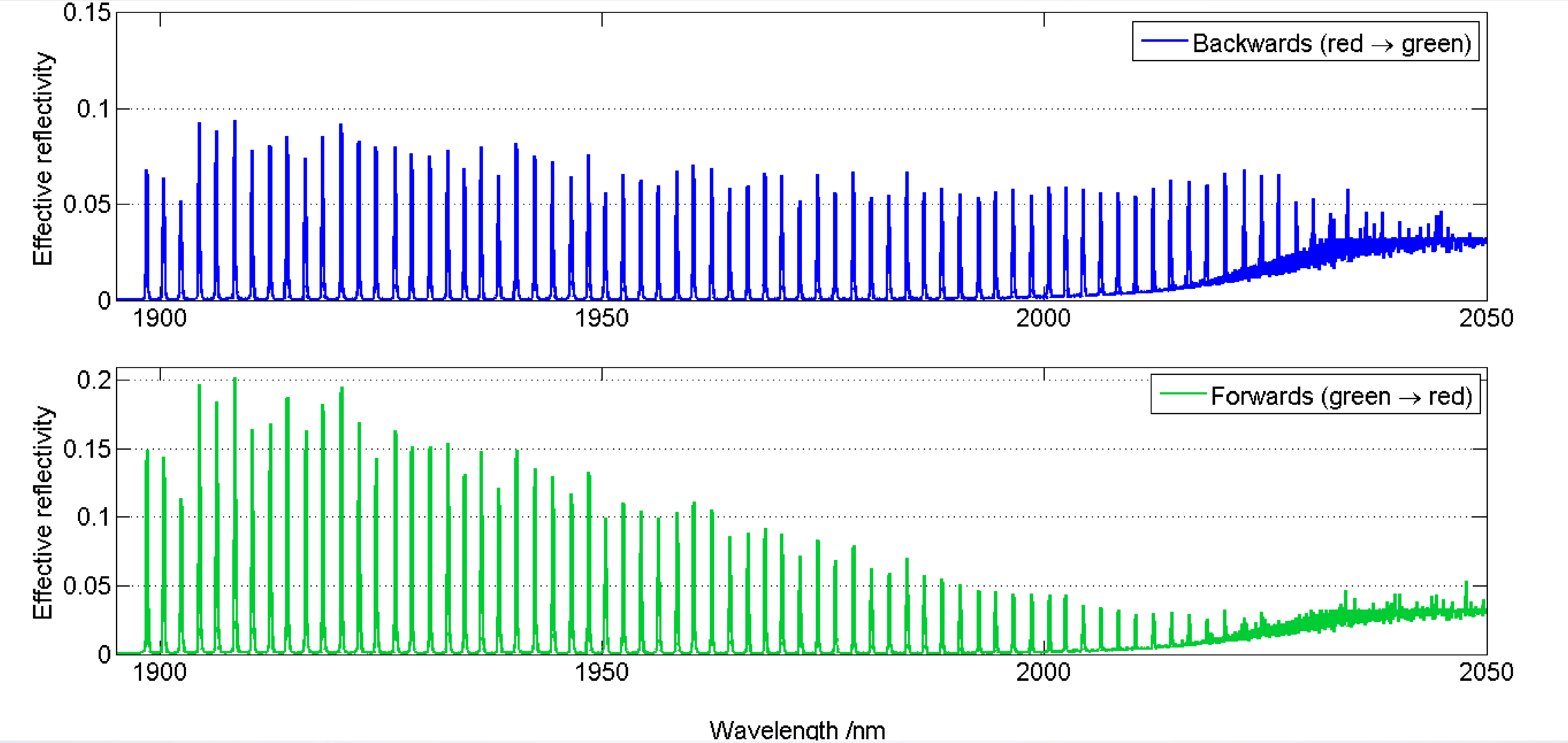
- ☺ Great **spectral flexibility** for individual tuning characteristics
  ⇨ **Ultra-wide tuning ranges**, scalable resolution, calibrated emission lines
- ☺ **Excellent stability of emission wavelength**
- ☺ monolithic filter design ⇨ **no alignment, no maintenance, robust**
- ☺ Electrically controlled ⇨ **programmable**, no moving parts in setup
- ☺ Adjustable pulse durations (ns range)
- ☺ Fast sweep times

Appendix: Reflectivity Spectrum HR FBG Array

- Reflectivity over Wavelength, fiber: PM1550-XP



Appendix: Reflectivity Spectrum nonPM DTG Array



Appendix: Nonlinear spectral broadening – source

- SBS → pulse too short (<100ns)
- SRS
  - Limiting @2µm → propagation losses in fiber
  - g_R~1/λ → shouldn‘t be a problem @2µm with 2m of fiber
  - No shift to shorter wavelengths
- SPM → B-Integral
  - $B = \frac{2\pi}{\lambda}\int_0^{L(AF)} n_2\, I(z)dz \;\approx \frac{2\pi}{\lambda} n_2 \frac{P}{\pi/_4 MFD^2} L_{eff} = B(P)$
  - n_2= 3e-16 cm²/W (@1.55µm), MFD = 10µm, L_{eff} = 2m (AF: 5m), λ=1950nm

    ➢B(300W) = 0.74 ; **B(406W) = 1**; B(500W)**=1.23**
  - Asymmetry due to reabsorption?
  - Main peak should broaden before side peaks arise
- ASE due to reabsorption (would explain the asymmetry)
- FWM → fits to observations in spectrum with DTG array

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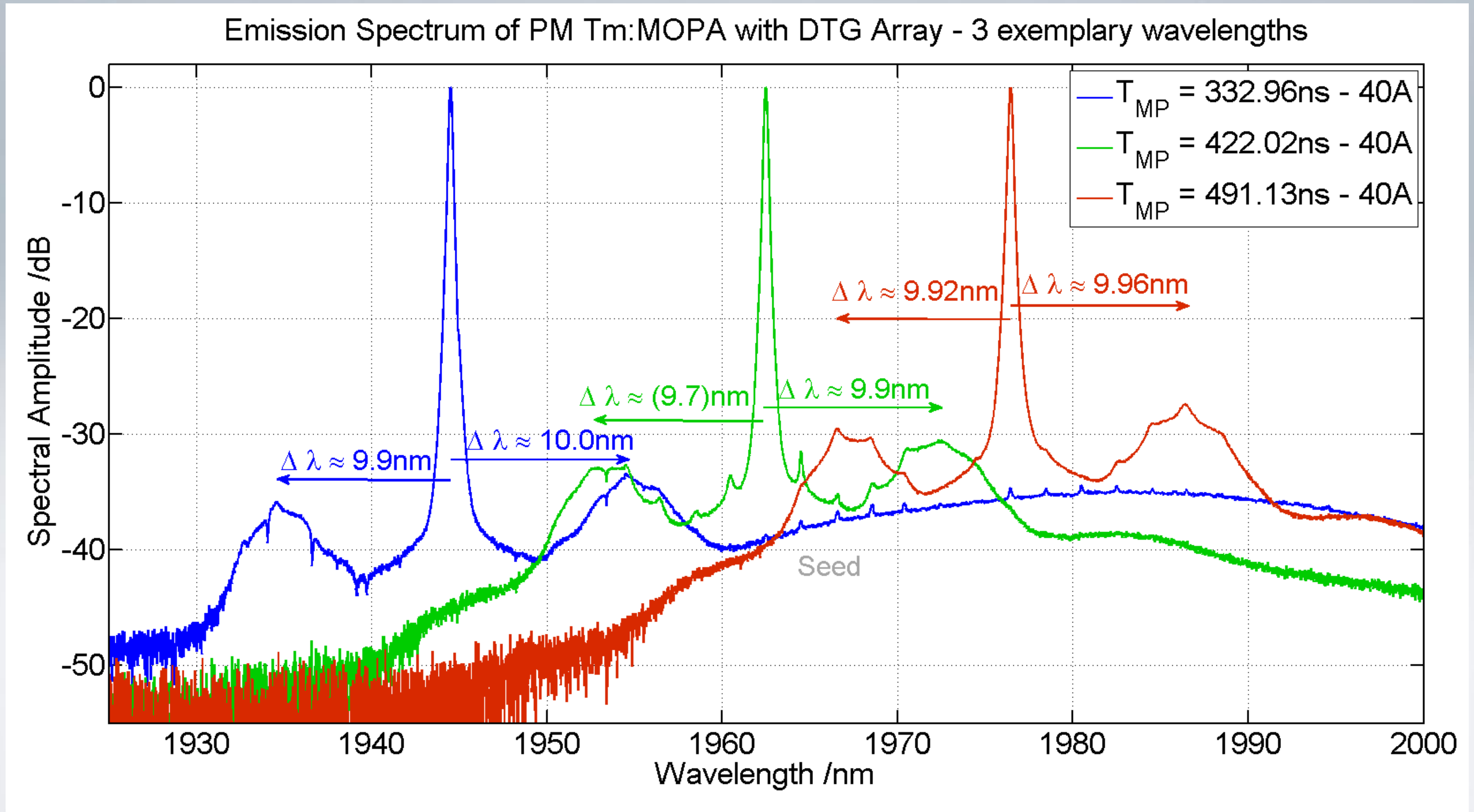
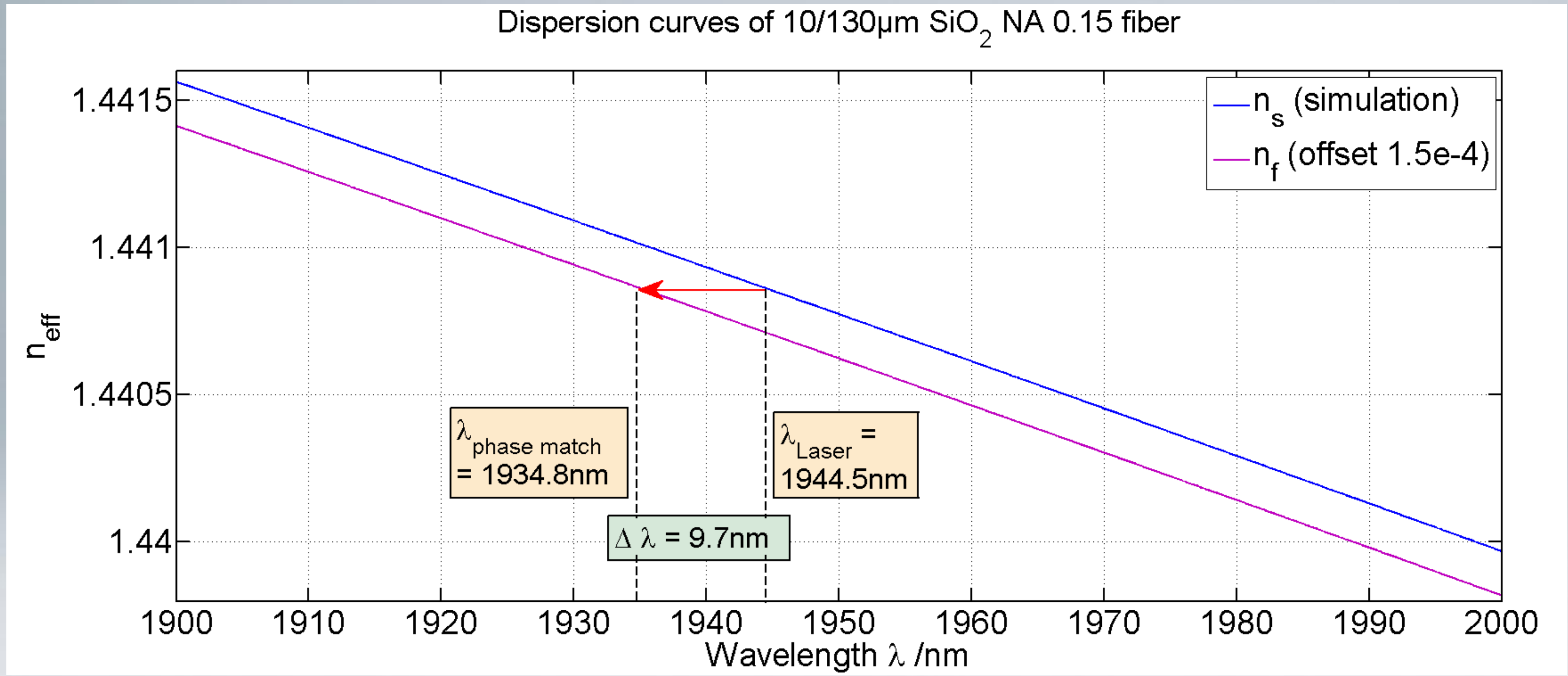
Appendix: FWM in Emission Spectra

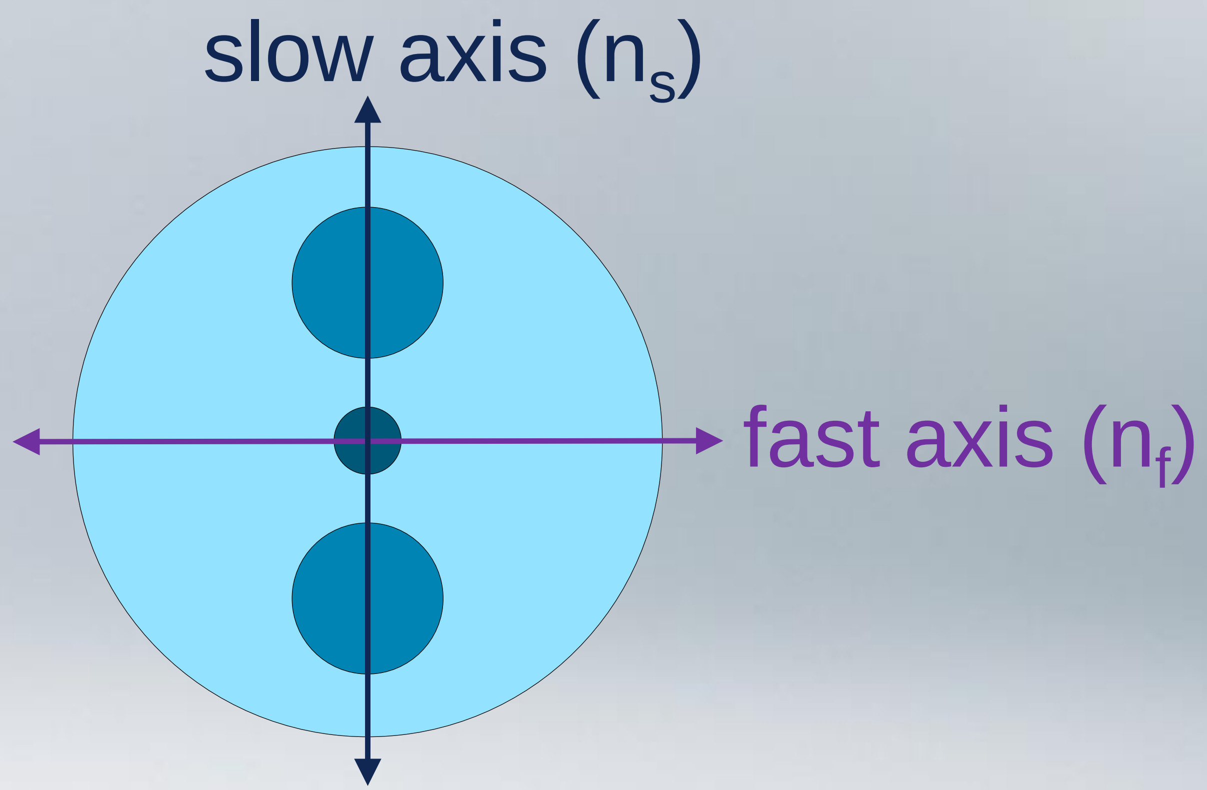
- 2 peaks grow nonlinear with power next to the laser line (symetric)
- Frequency shift (@1944nm): $\boldsymbol{\Delta v = 747GHz \; \ldots 824GHz}$
- Energy conservation is roughly satisfied



Appendix: FWM as source of spectral broadening

- Phase matching condition for fixed frequency shift of peaks???
  - phase matching by other polarization direction:





- Example: Peak @ 1944.49nm with Dispersion Data from Adrian
  - $\mathbf{\Delta\lambda\ (n_f = n_s) = 9.7nm}$ **(Experiment: ~9.9nm)**
  - Alternative: $\Delta\lambda_{experiment} = 9.9\text{nm} \rightarrow \Delta n = 1.57\text{e-}4$ (Fiber data: 1.5-e4)

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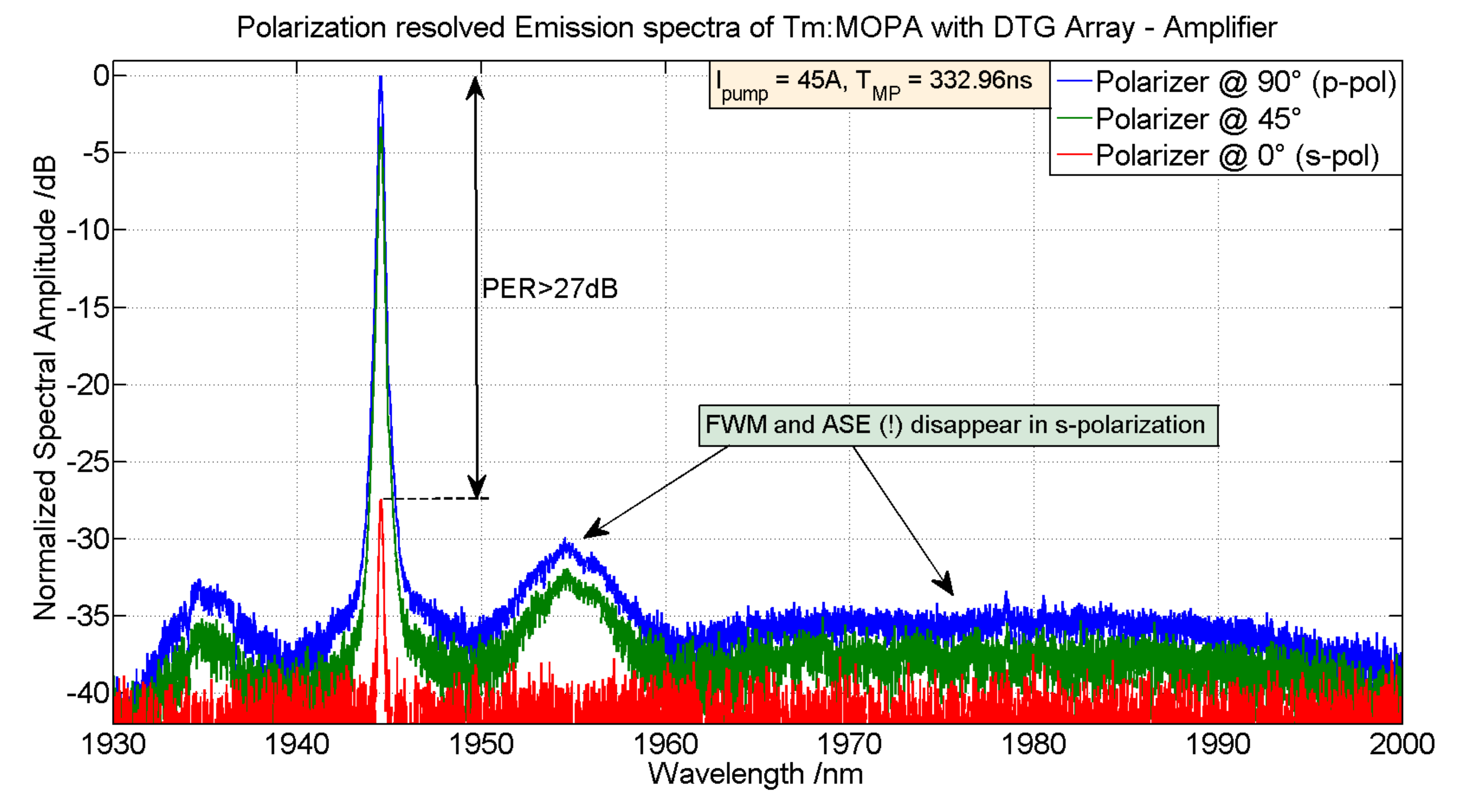
Appendix: Experimental Proof

- If FWM is triggered by phase matching with other polarization axis, the FWM signal should be mostly in other polarization orientation!



→ **Not the case… ☹**

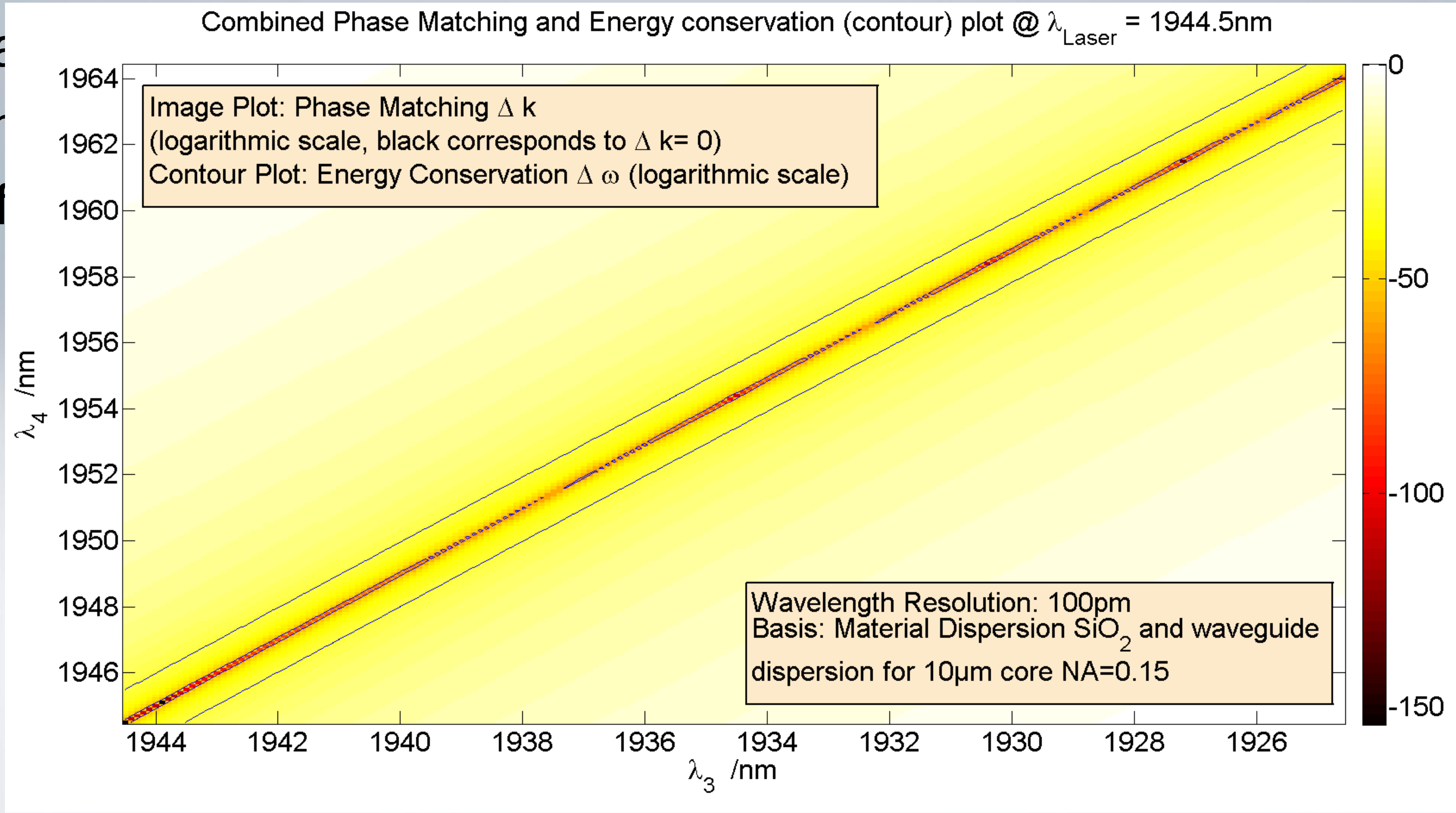
Is measurement correct?

(also ASE disappears)

And: FWM is polarization dependent

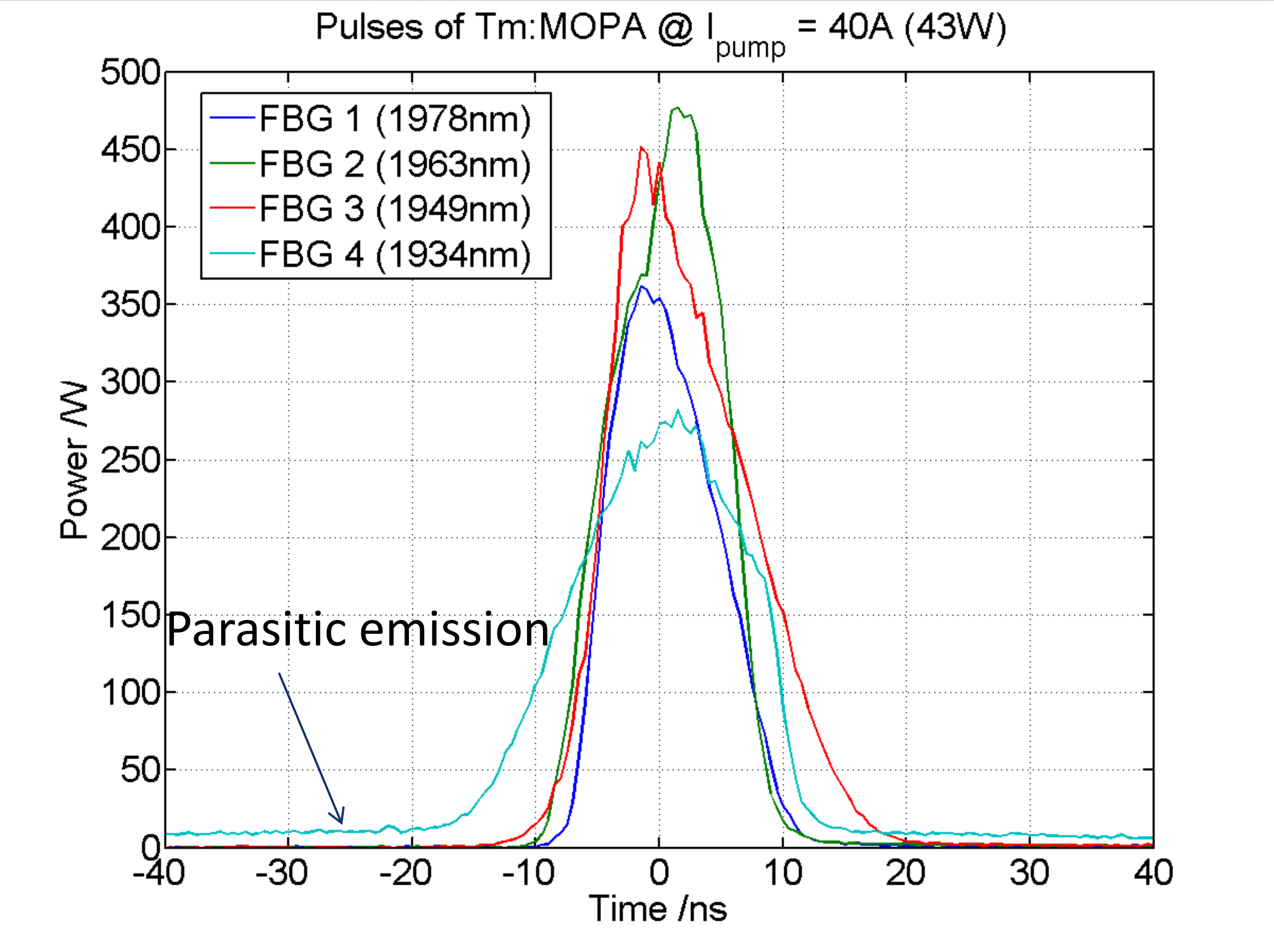
Appendix: General Phase Matching of FWM

- Within the resolution limit: Phase matching ($\Delta k = 2k_1 - k_3 - k_4 = 0$) and Energy conservation ($\Delta\omega = 2\omega_1 - \omega_3 - \omega_4 = 0$) are equivalent
- No distinct dispersion character for wavelength shift of 10nm
- Phase Ma … r dependent
- Theory im … uracy of β_2?)
- Source of



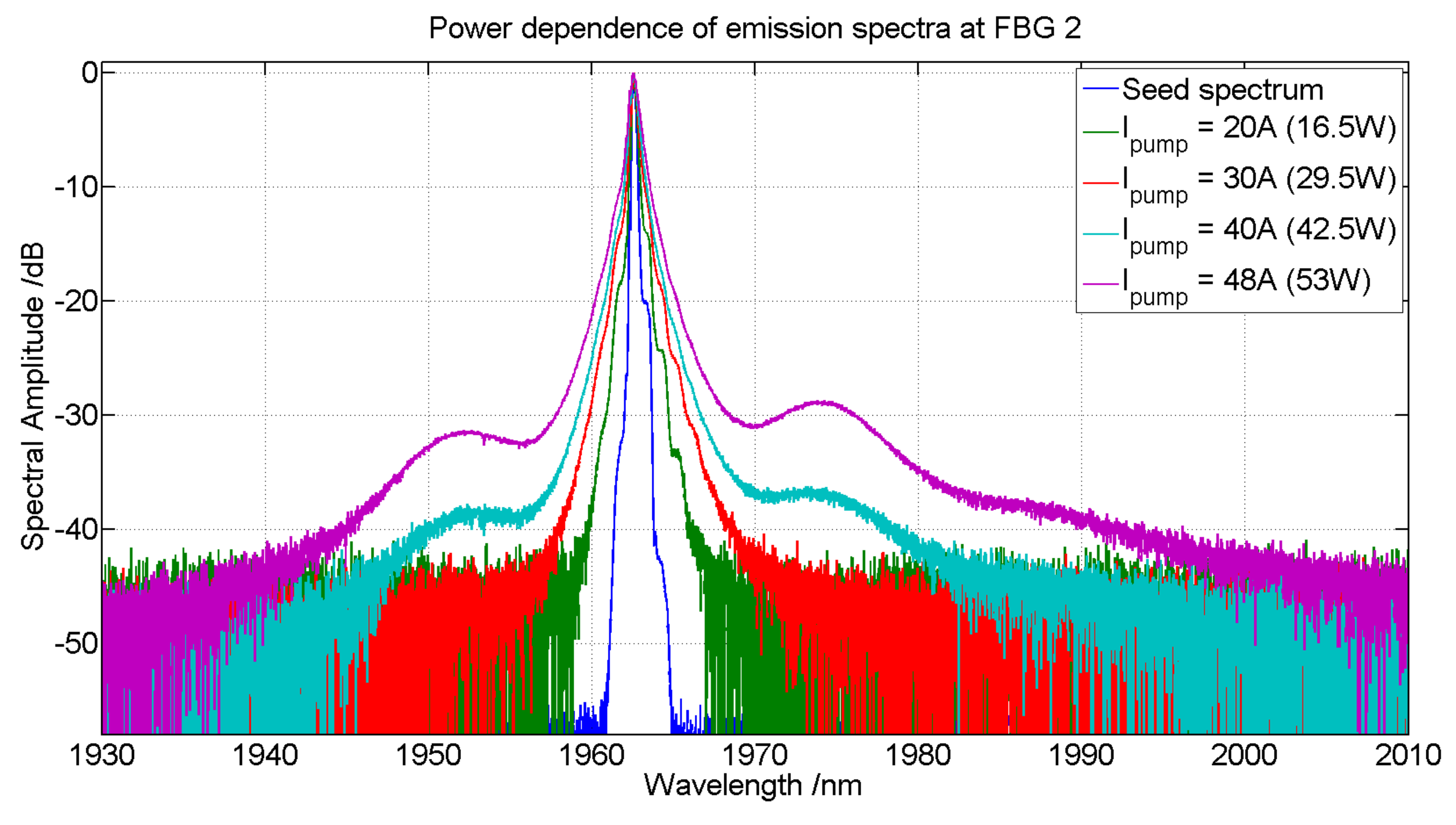
Appendix: Peak power comparison for different wavelengths

- Due to changing repetition rate, pulse duration & spectral gain → peak power varies
- Pulse duration FBG 1-4: 11ns, 11ns, 12.5ns & 17ns (short pulse regime)



Appendix: Power dependence of NL effects

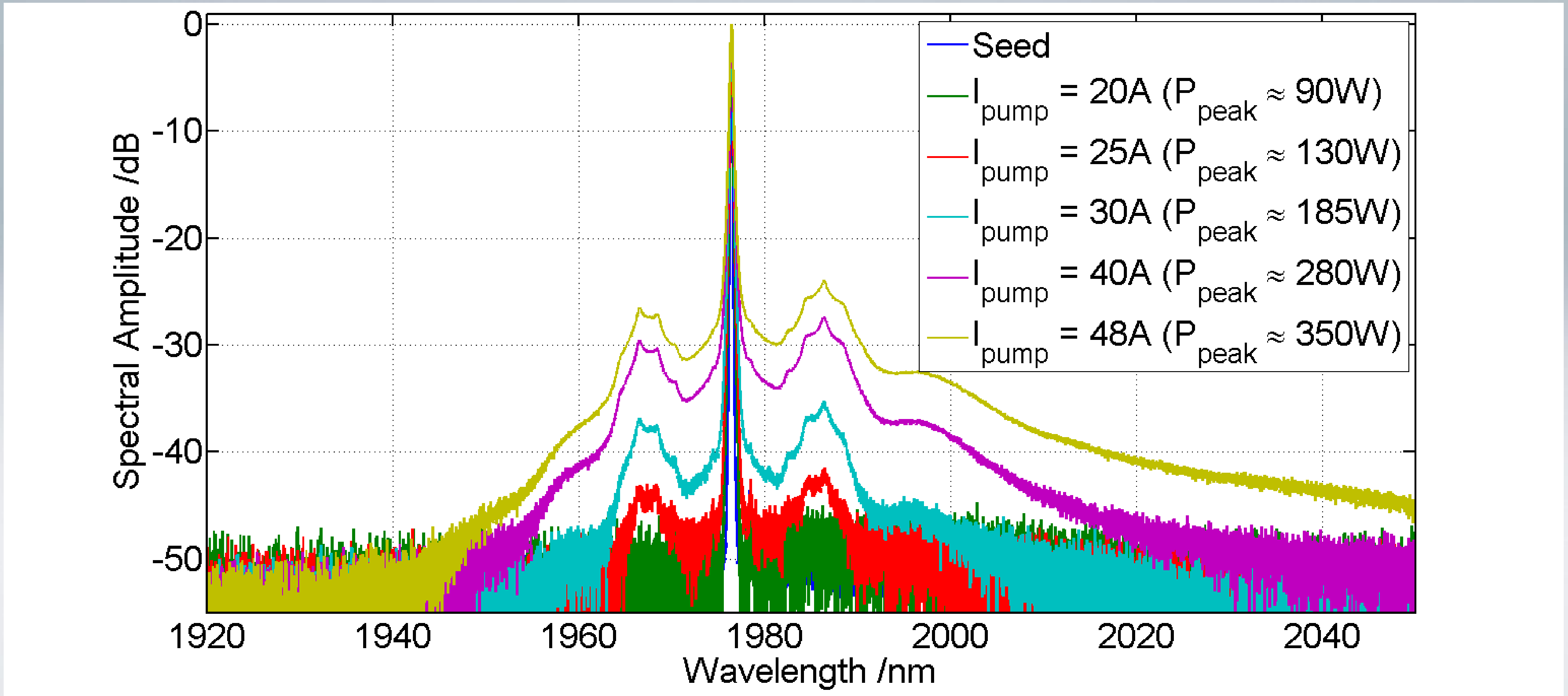
- FWM starts to become significant from average powers above 22W (in short pulse regime, this corresponds to 450W peak power)



Normalized plot

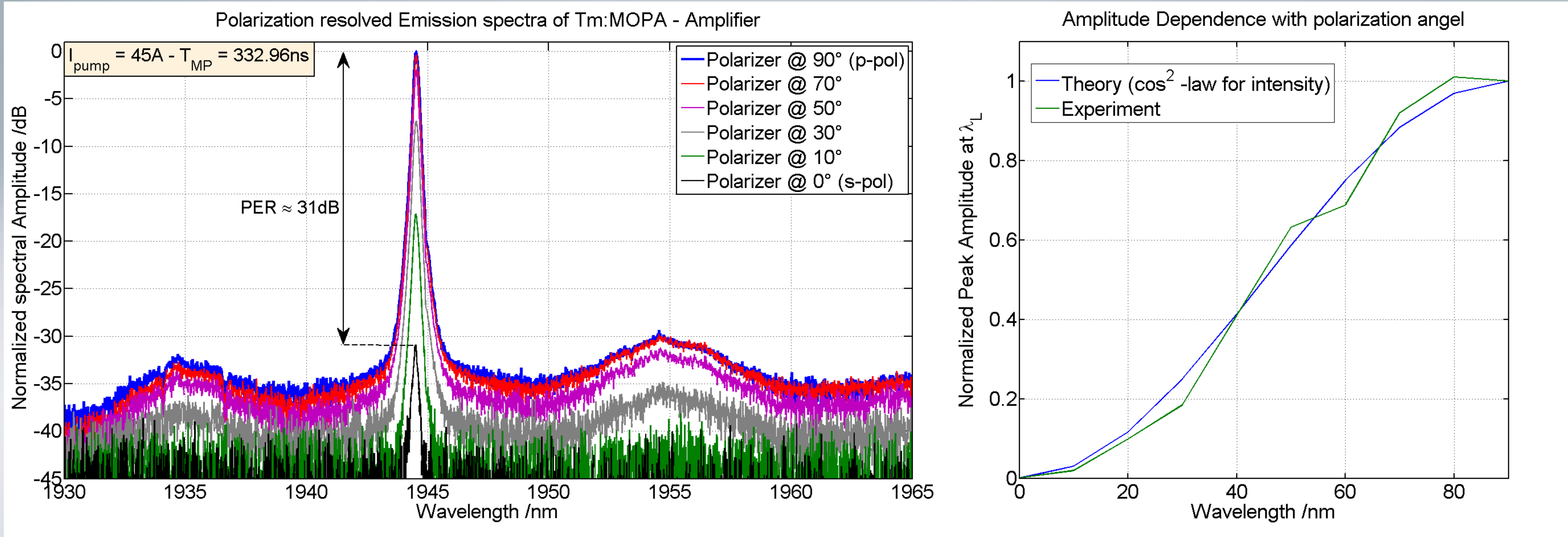
Appendix: Nonlinear Broadening

- Emission peak stays narrow (FWHM <250pm), but sidewings grow
- FWM seems to be source → discussion later…



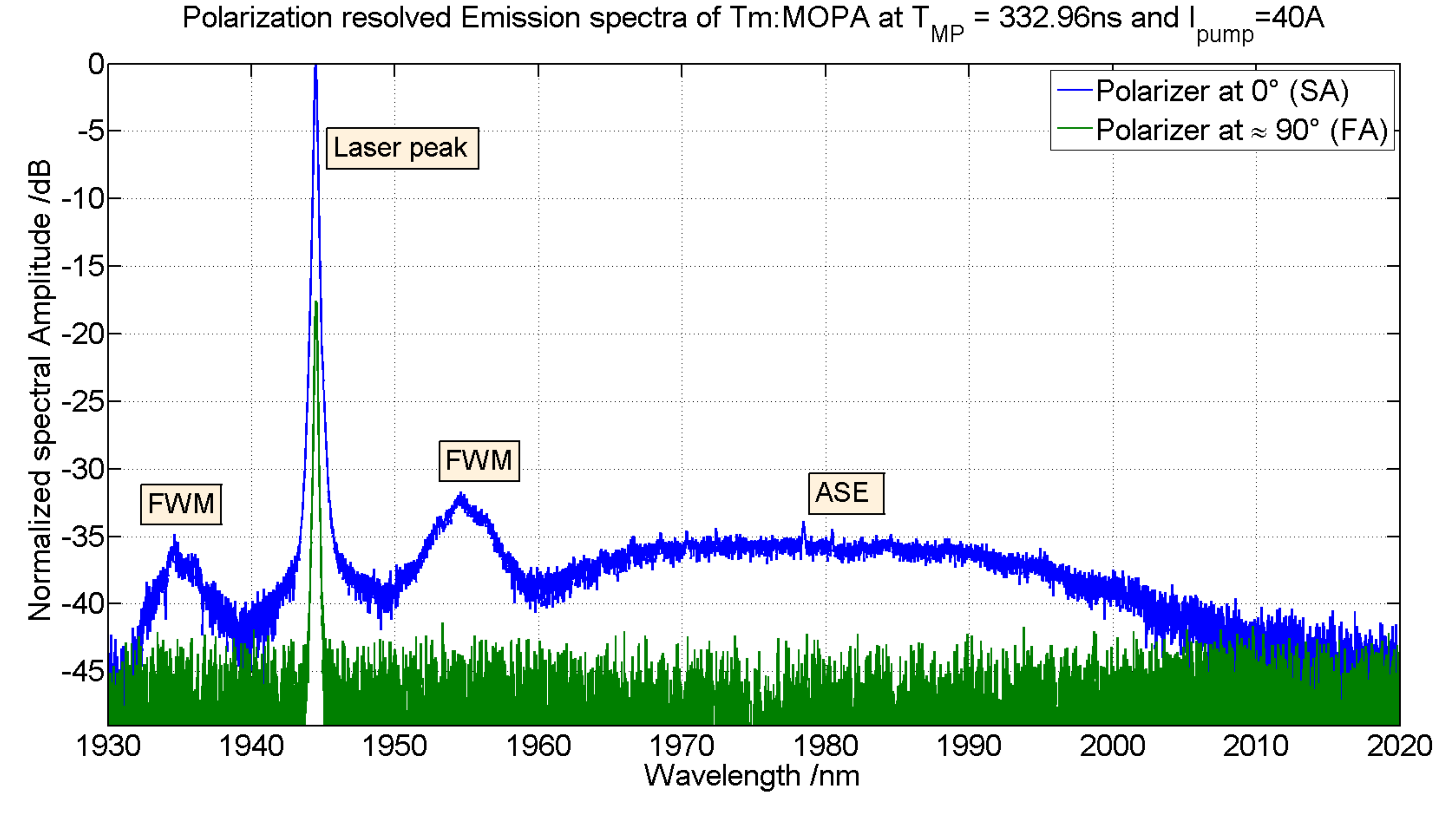
Appendix: Polarization dependent Spectrum

- Spectral PER =31dB!
- Amplitude follows cos² - Intensity law over polarization angel



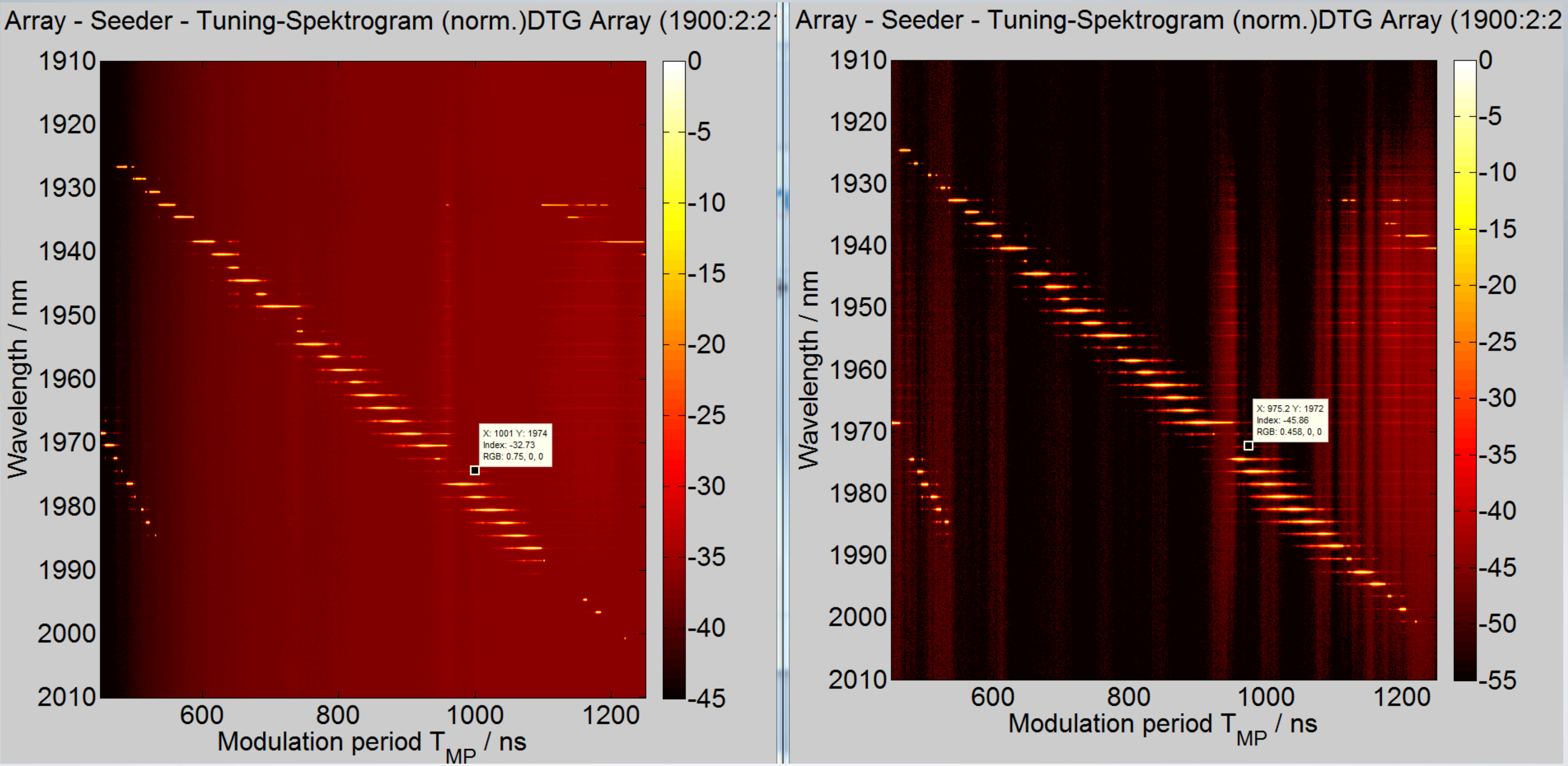
Appendix: Pol. Resolved spectra → ASE

- ASE really disappears with other polarization angel… why?



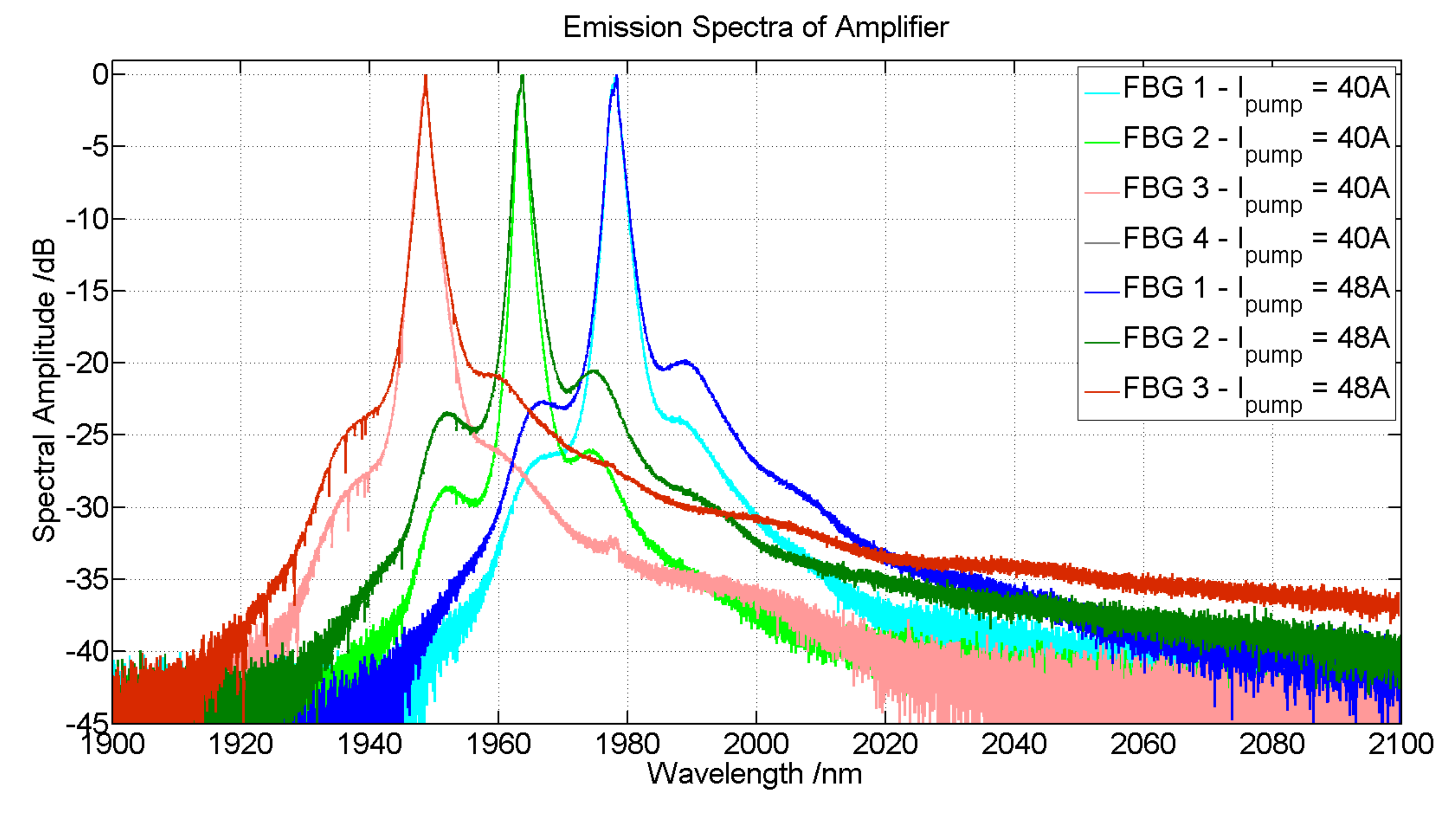
Appendix: random rotation of Polarization

- Why did the laser not start to oscillate over all FBGs in the same way



Appendix: Reproducibility of spectra

- <u>2nd measurement</u>:
  - No spiky peaks anymore
  - Pronounced FWM character (due to narrower emission line)
  - Less nonlinear broadening → maybe not shortest pulse regime or less pulse fluctuations?!



Normalized plot

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Appendix: Pulse properties DTG Array

- Parabolic-like shape
- Pulse duration ~ 42ns
- In short pulse regime: pulse duration of 20ns possible (further scaling of peak power possible)
- Pulse duration is longer than with HR FBG array!