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Haiyang Zhang, Hongzhi Yang, Marc Brunel, Marc Vallet, Changming Zhao,
Suhui Yang

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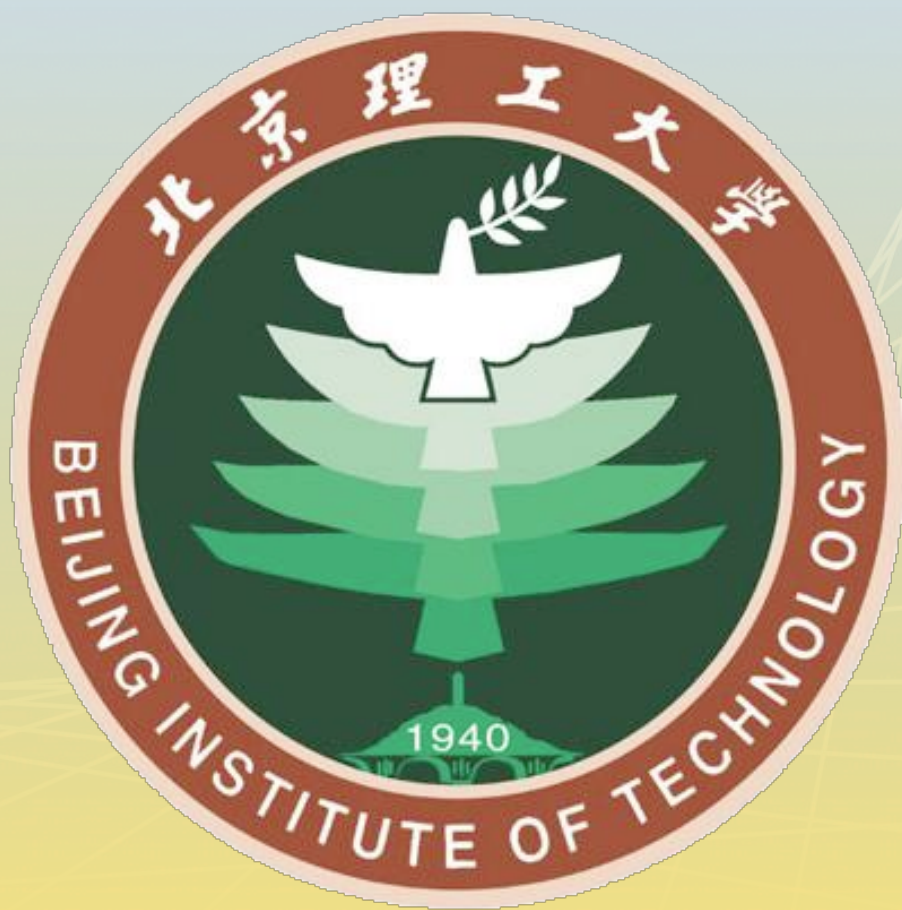
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Fiber frequency-shifting loop for RF up-conversion and waveform generation

H. Zhang,¹ H. Yang,¹ M. Brunel,² M. Vallet,² C. Zhao,¹ and S. Yang¹

¹Beijing Institute of Technology, School of Optoelectronics

²Institut FOTON, Université de Rennes 1–CNRS UMR 6082

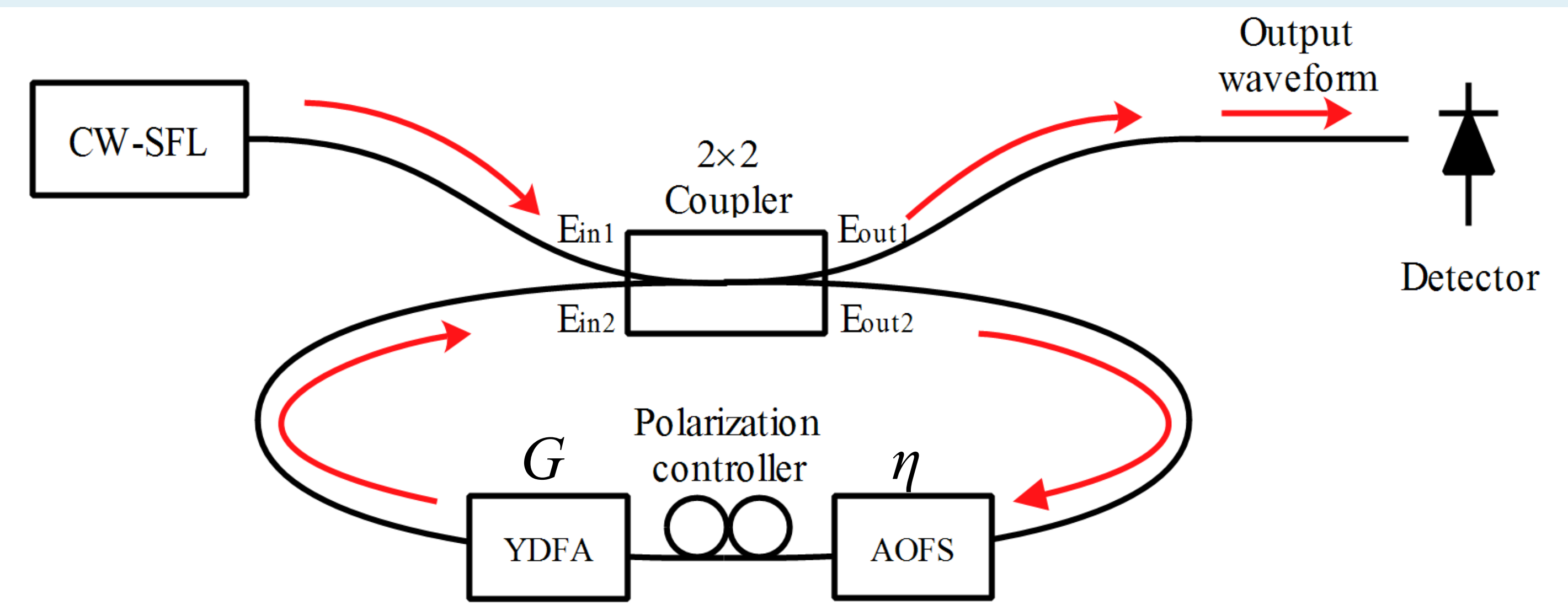
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Introduction

- ring interferometer + frequency-shifter + amplifier [1-4]
=> self-heterodyning, Frequency-Shifted Feedback laser, real-time Fourier Transform, wavelength scan, etc.
- microwave photonics context (lidar-radar for example) [5-8]
=> RF up-conversion, waveform generation
- Here high-harmonic RF beats, sub-threshold operation (\neq FSF laser)
+ all-fibered experiment @ 1064 nm vs simulation



Model: time delayed interferences

$$\begin{bmatrix} E_{out1} \\ E_{out2} \end{bmatrix} = \begin{bmatrix} t_{11} & t_{12} \\ t_{21} & t_{22} \end{bmatrix} \begin{bmatrix} E_{in1} \\ E_{in2} \end{bmatrix}$$

- $\lambda = 1064$ nm (YDFA with gain G)
- Acousto-Optic Frequency Shifter
 $f_{AO} = 200$ MHz \pm 5 MHz, $\eta = 0,4$
- ~ 20 m loop ($\tau = 5$ ns)

Inside the loop:

$$E_{out2}(t) = t_{21} \sum_{p=0}^{\infty} (t_{22}\gamma)^p E_{in1}(t - p\tau) e^{i2\pi f_{AO} p(t-\tau)} e^{-i\pi f_{AO} p^2 \tau} \quad \text{with } \gamma = \sqrt{\eta G} e^{i\varphi}$$

Output field:

$$\begin{aligned} E_{out1}(t) &= t_{11} E_{in1}(t) + t_{12} E_{in2}(t) \\ &= t_{11} E_{in1}(t) + t_{12} \gamma E_{out2}(t - \tau) e^{i2\pi f_{AO}(t-\tau)} \\ &= t_{11} E_{in1}(t) + t_{12} \gamma t_{21} \sum_{p=1}^{\infty} (t_{22}\gamma)^{p-1} E_{in1}(t - p\tau) e^{-i\pi f_{AO} p\tau} e^{i2\pi f_{AO} p t} e^{-i\pi f_{AO} p^2 \tau} \end{aligned}$$

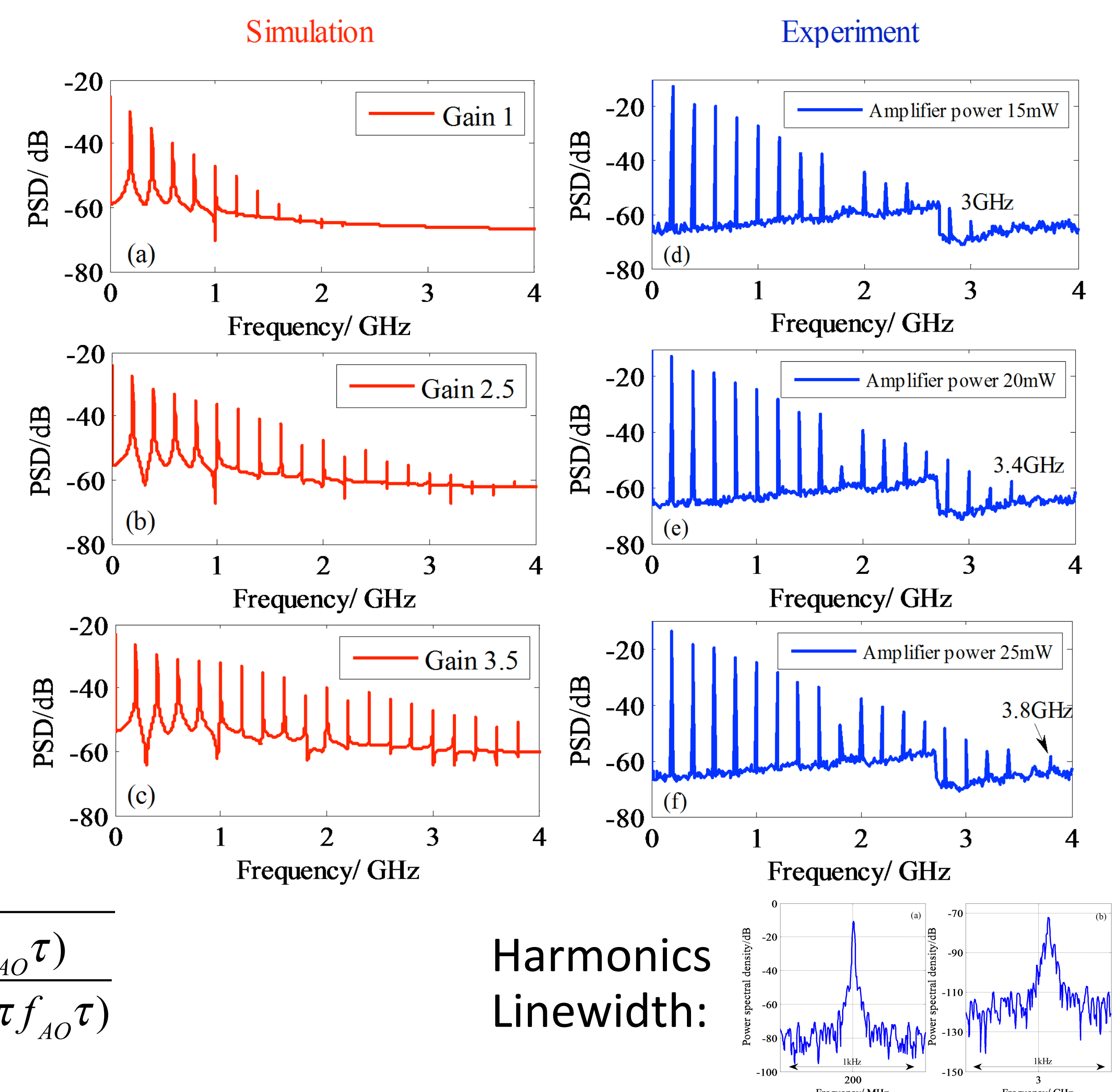
Output power:

$$P_{out}(t) = \left| t_{11} + t_{12} \gamma t_{21} \sum_{p=0}^{\infty} (t_{22}\gamma)^p e^{i2\pi f_{AO}(p+1)t} e^{-i\pi f_{AO}(p+2)(p+1)\tau} \right|^2 P_{in}$$

$$P_{out}(t) = P_0 + \sum_{n=1}^{\infty} \left[P_n e^{i2\pi n f_{AO} t} + c.c. \right] \quad \text{with } |P_n| = (\Gamma T_{11})^{n/2} T_{12} \sqrt{\frac{(1-\Gamma)^2 + 4\Gamma \sin^2(n\pi f_{AO} \tau)}{(1-\Gamma T_{11})^2 + 4\Gamma T_{11} \sin^2(n\pi f_{AO} \tau)}}$$

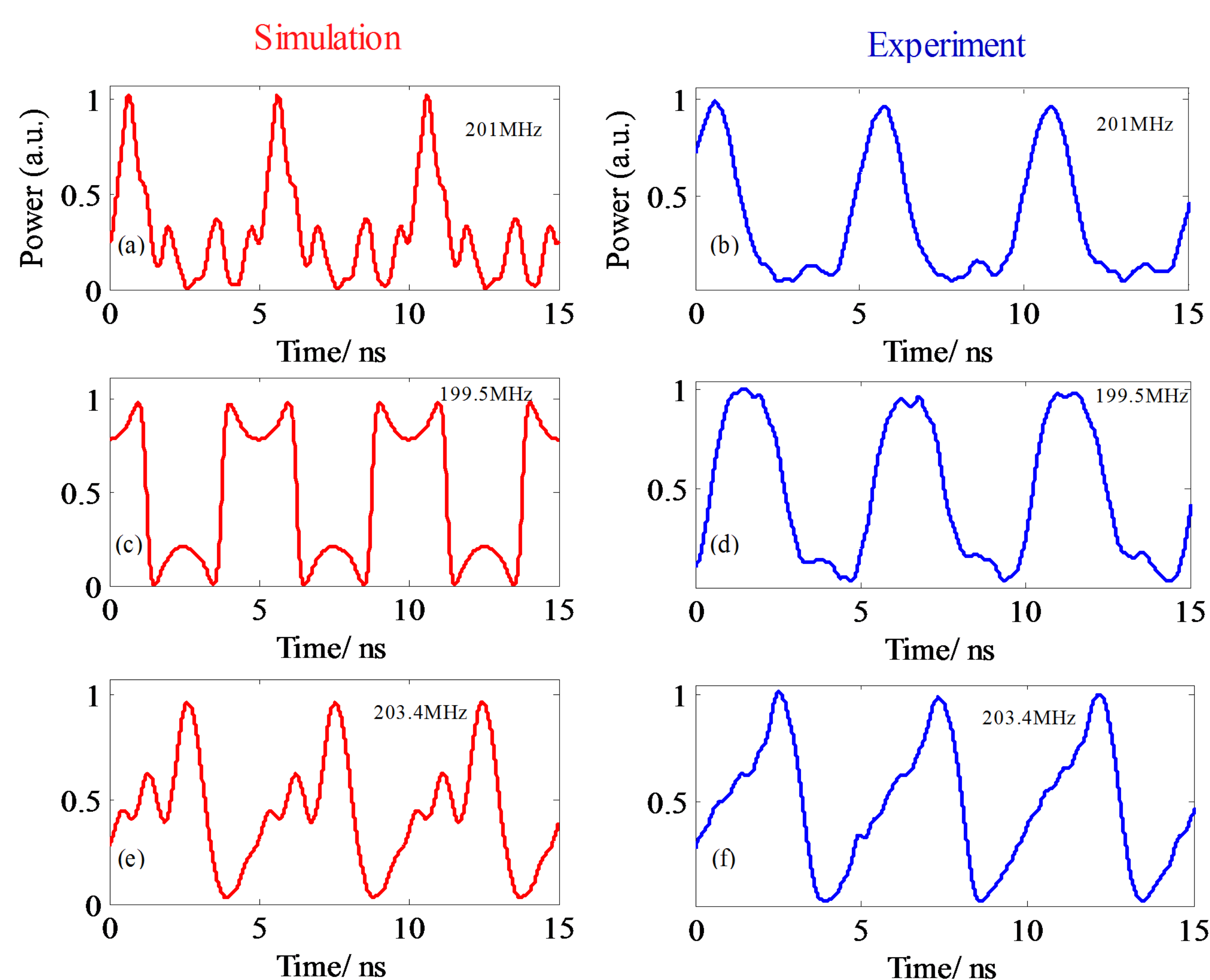
$$\Gamma = |\gamma|^2$$

Frequency domain: harmonics vs gain

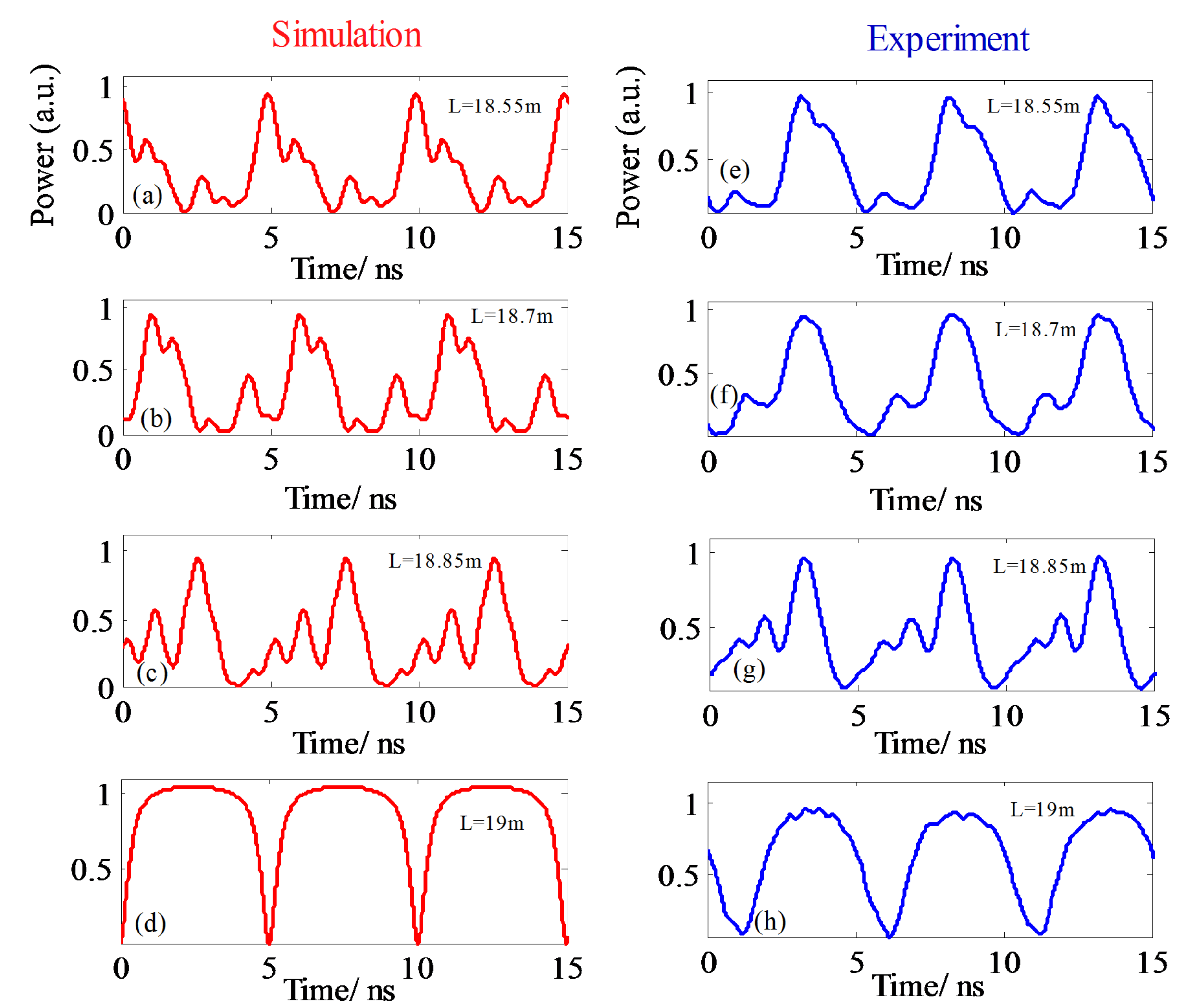


Harmonics
Linewidth:

Time domain: waveform depends on the RF harmonics phases ($n\pi f_{AO} \tau$)



Influence of frequency shift on the waveform



Influence of the loop length on the waveform (steps of 15 cm)

Conclusion

- RF enhancement x15 (here up to ~ 4 GHz)
- programmable and integrable scheme
- Perspectives**
- + SHG => green source for underwater [5-6]
- Ultra-low Doppler frequency shifts
- All-fibered experiment @ 1550 nm
- Above threshold (solitons, mode-locking, etc)

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