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## A fiber frequency-shifting loop for RF up-conversion and waveform generation

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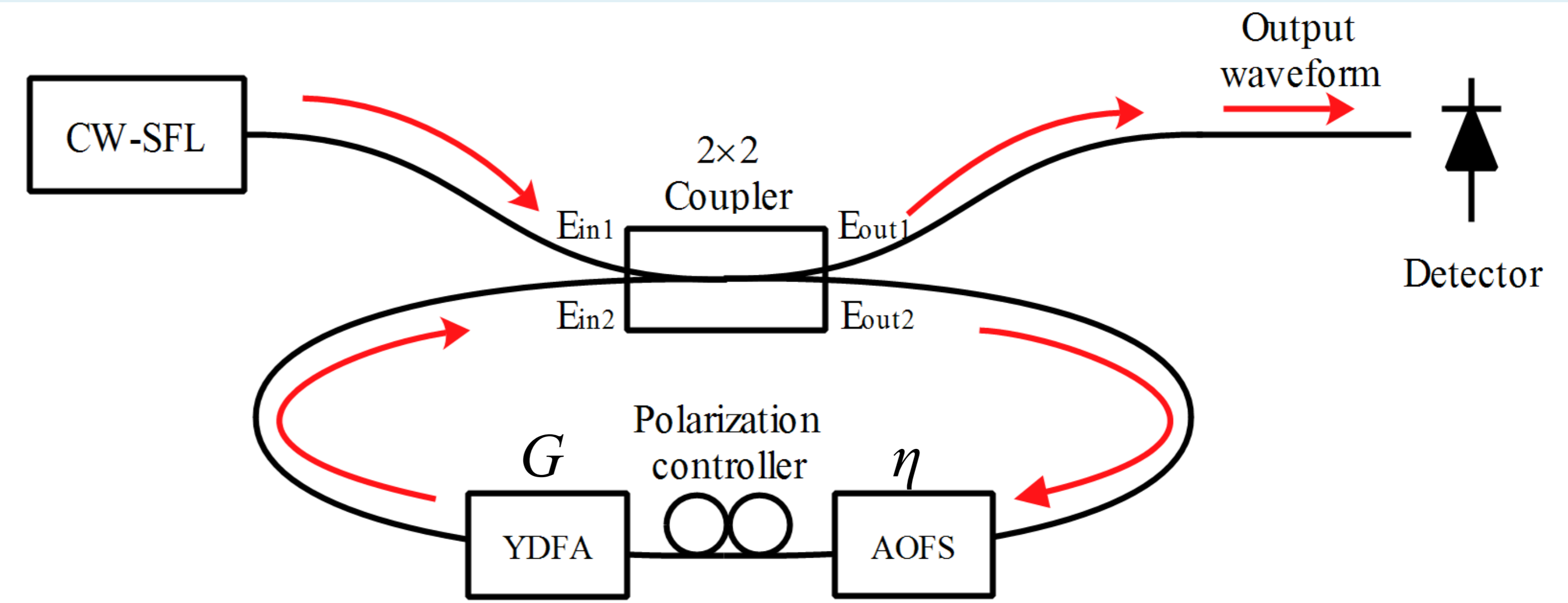
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## Introduction

- 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,  $\eta = 0,4$
- $\sim 20$  m loop ( $\tau = 5$  ns)

Inside the loop:

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

Output field:

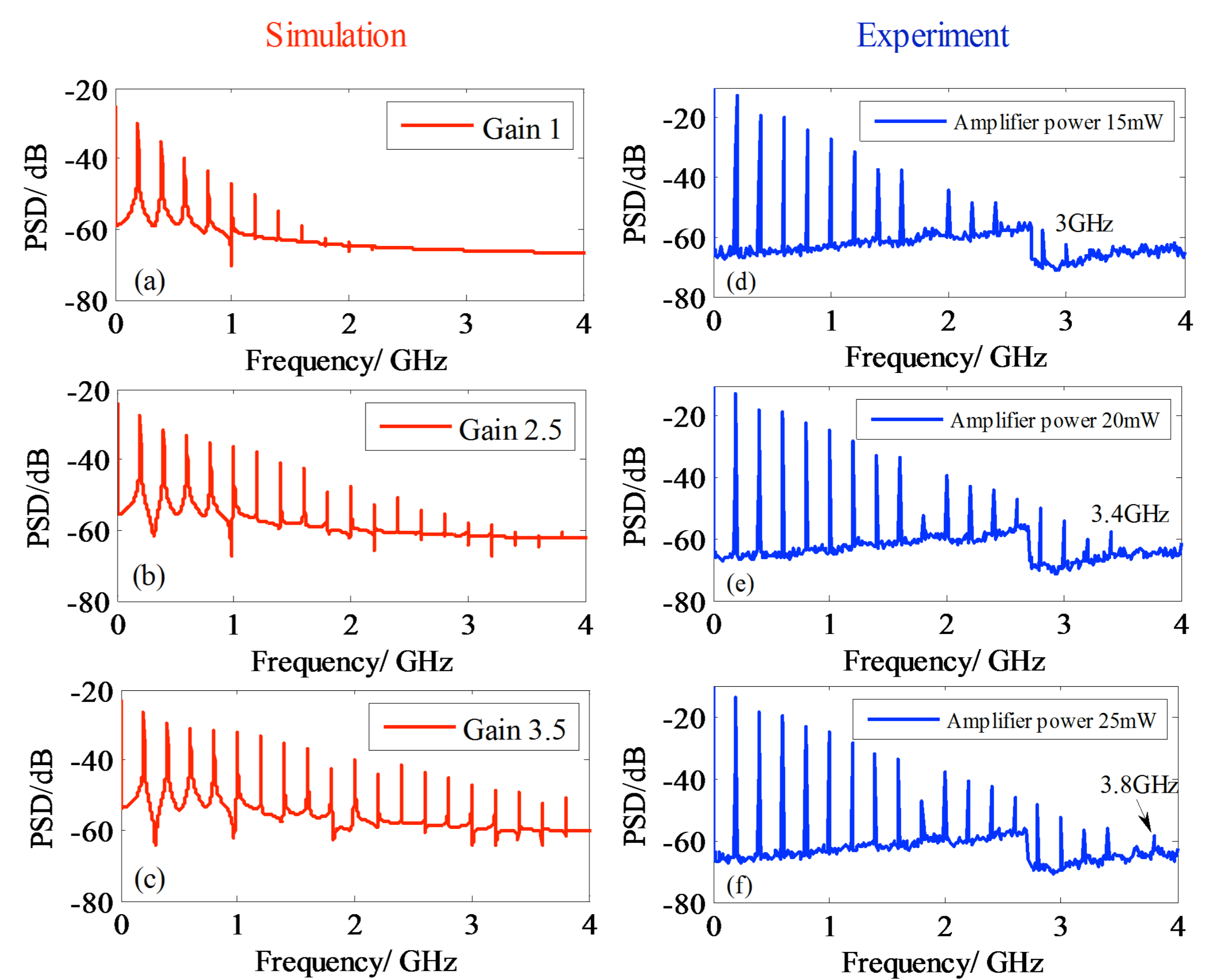
$$\begin{aligned} E_{out1}(t) &= t_{11}E_{in1}(t) + t_{12}E_{in2}(t) \\ &= t_{11}E_{in1}(t) + t_{12}\gamma E_{out2}(t-\tau) e^{i2\pi f_{AO}(t-\tau)} \\ &= t_{11}E_{in1}(t) + t_{12}\gamma t_{21} \sum_{p=1}^{\infty} (t_{22}\gamma)^{(p-1)} E_{in1}(t-p\tau) e^{-i\pi f_{AO}p\tau} e^{i2\pi f_{AO}pt} e^{-i\pi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

Output power:

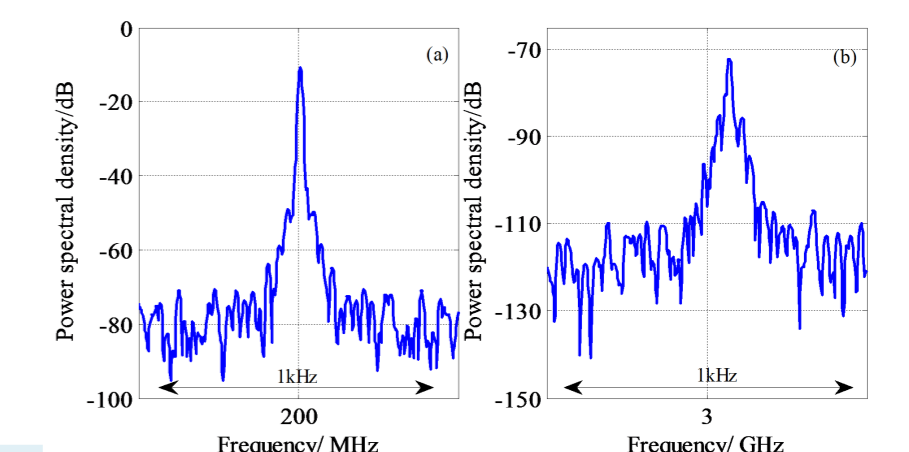
$$P_{out}(t) = \left| t_{11} + t_{12}\gamma t_{21} \sum_{p=0}^{\infty} (t_{22}\gamma)^p e^{i2\pi f_{AO}(p+1)t} e^{-i\pi f_{AO}(p+2)(p+1)\tau} \right|^2 P_{in}$$

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

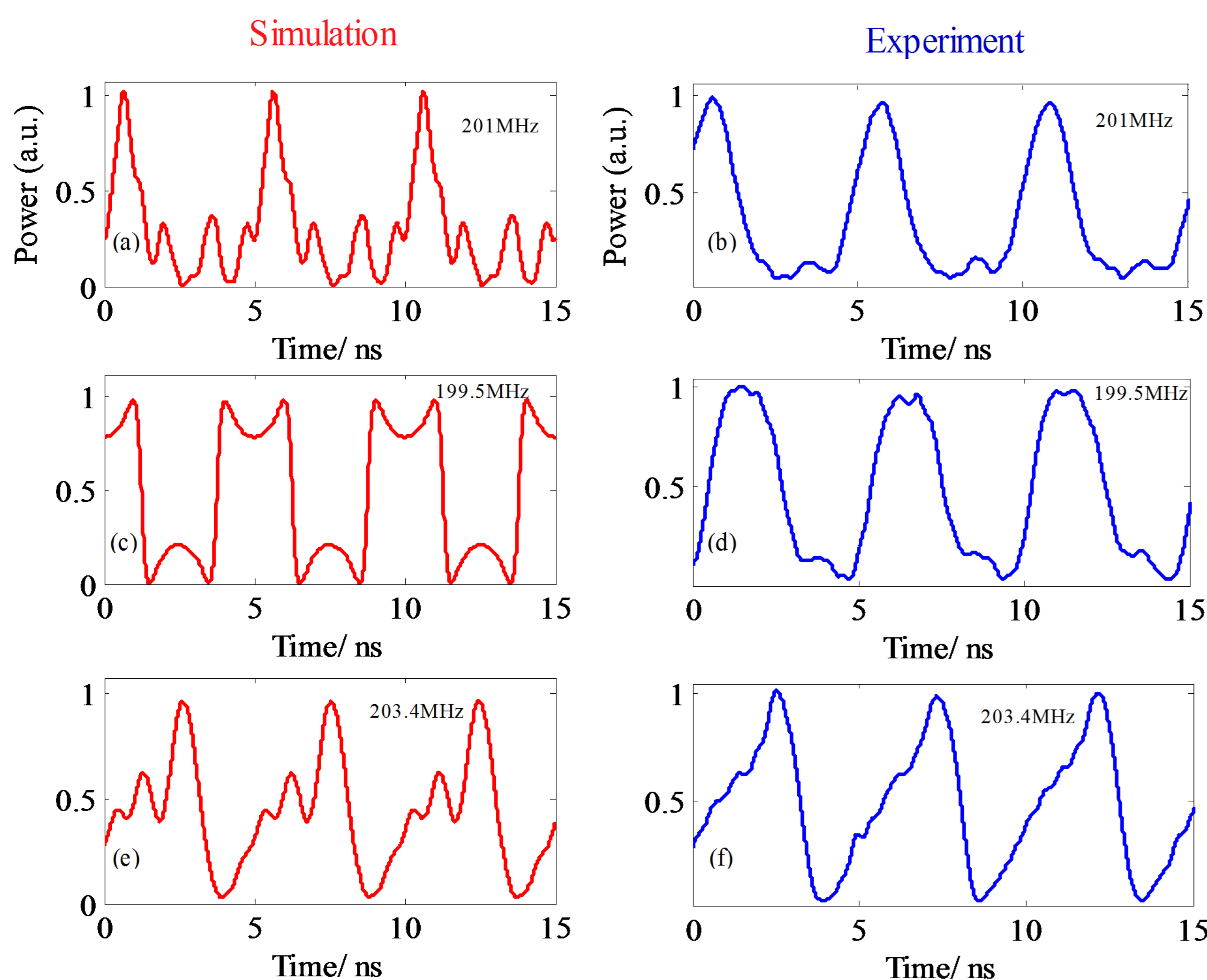
## Frequency domain: harmonics vs gain



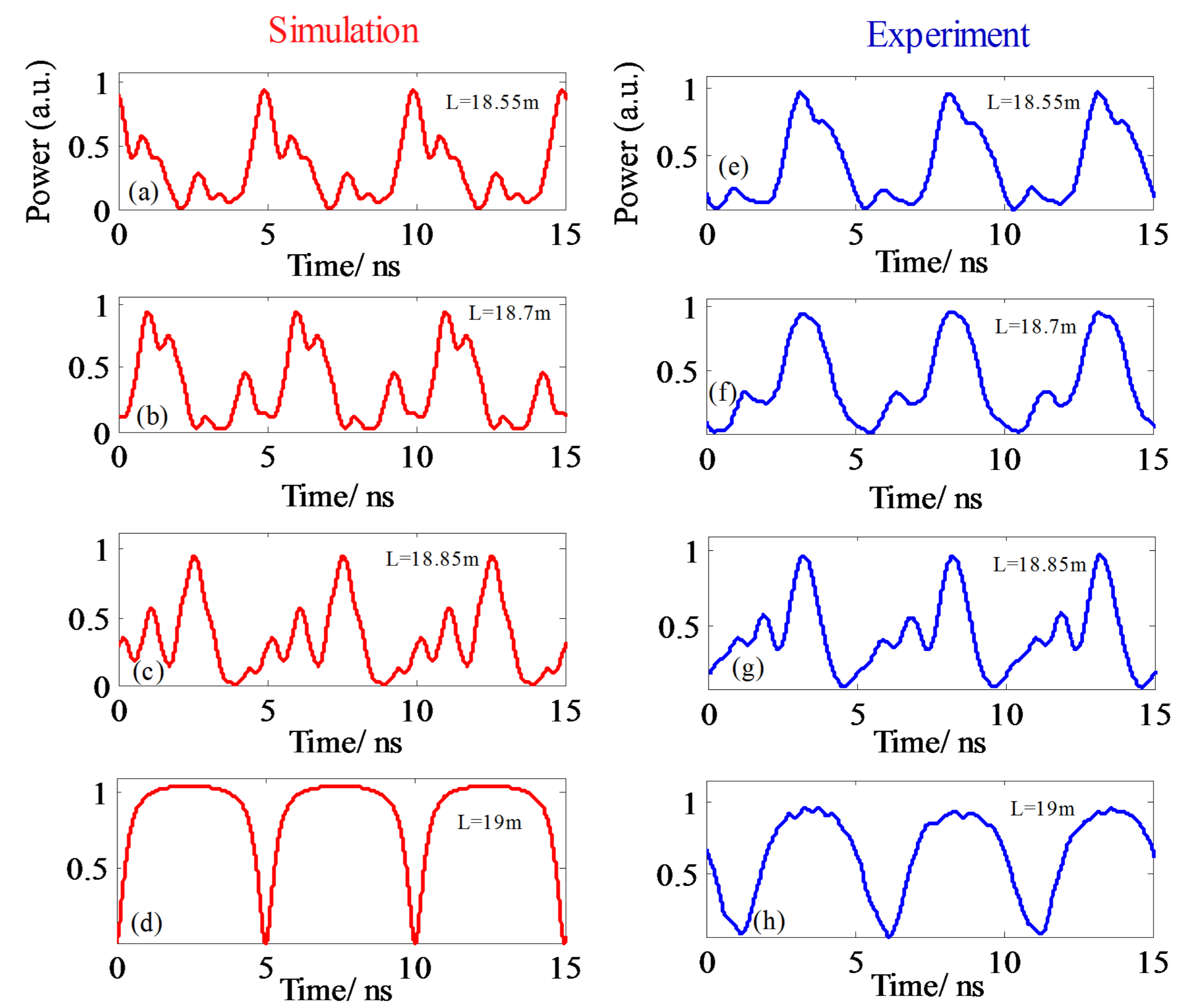
Harmonics  
Linewidth:



## 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  $\sim 4$  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)

## References

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