Control of the Group Velocity of Light in EDFs Via the Modulation Frequency

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Previous works

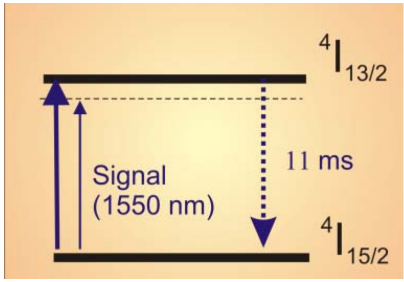
SL propagation in EDFs based on CPO

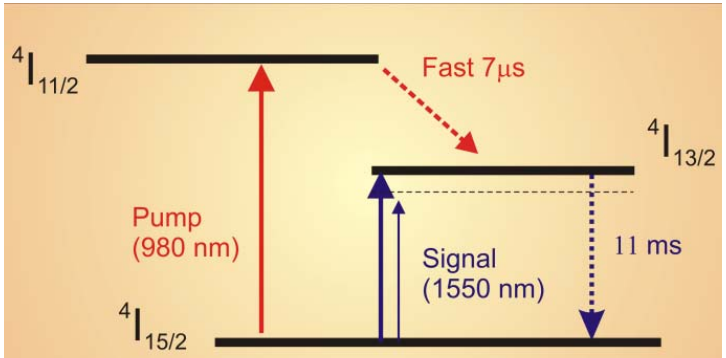
Schweinsberg et al., Europhys. Lett. **73**, 218 (2006)

L = 13 m

Er^{3+} ions $\rho = 1.78 \times 10^{24}\ \mathrm{m}^{-3}$ (Er 2dB/m)

$P_0 = 0.8\ \mathrm{mW}$





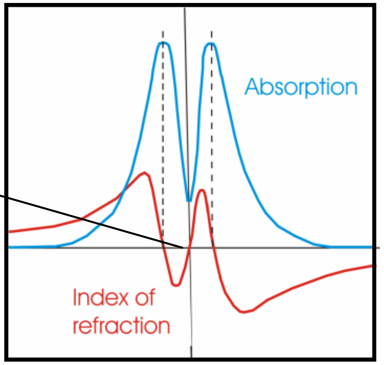
Signal $P_S = P_0 + P_m \cos(\omega_m t)$

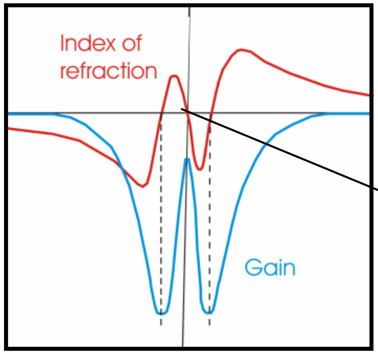
8%

Signal $P_S = P_0 + P_m \cos(\omega_m t)$

Pump P_p

SUBLUMINAL





SUPERLUMINAL

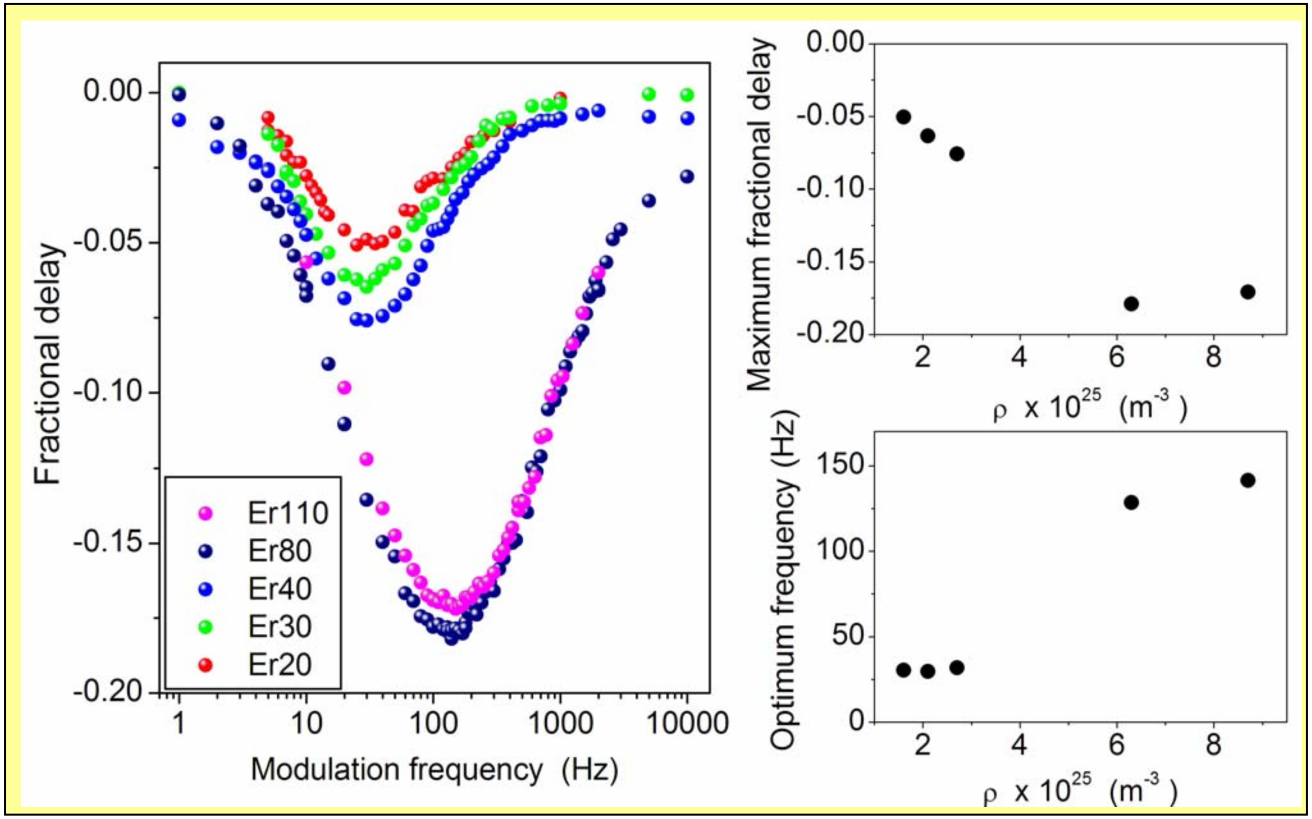
Previous works

SL propagation in EDFs based on CPO

Melle et al., Opt. Commun. **279**, 53 (2007)

L= 1 m

Er^{3+} ions $\rho = 1.6\times10^{25}\ \mathrm{m}^{-3} \rightarrow 8.7\times10^{25}\ \mathrm{m}^{-3}$ (Er 20dB/m) → (Er 110dB/m)



$P_0 = 0.5\ \mathrm{mW}$

Zhang et al., Opt. Commun. **281**, 2633 (2008)

Previous works

SL propagation in EDFs based on CPO

Schweinsberg et al., Europhys. Lett. **73**, 218 (2006)

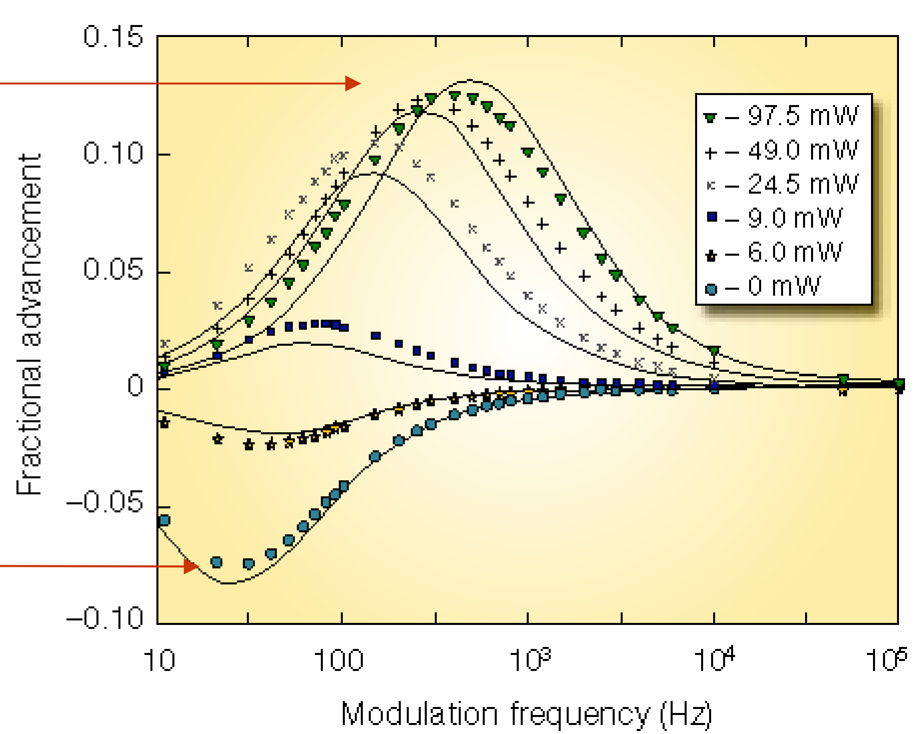
L = 13 m

Er^{3+} ions $\rho = 1.78\times10^{24}\ \mathrm{m}^{-3}$ (Er 2dB/m)

Transition sub- to superluminal upon INCREASING PUMP POWER

F ~ 0.125

F ~ -0.075



$$f_{opt} = \frac{1}{2\pi\tau}\left(1 + \hat{P}_0 + \hat{P}_p\right)$$

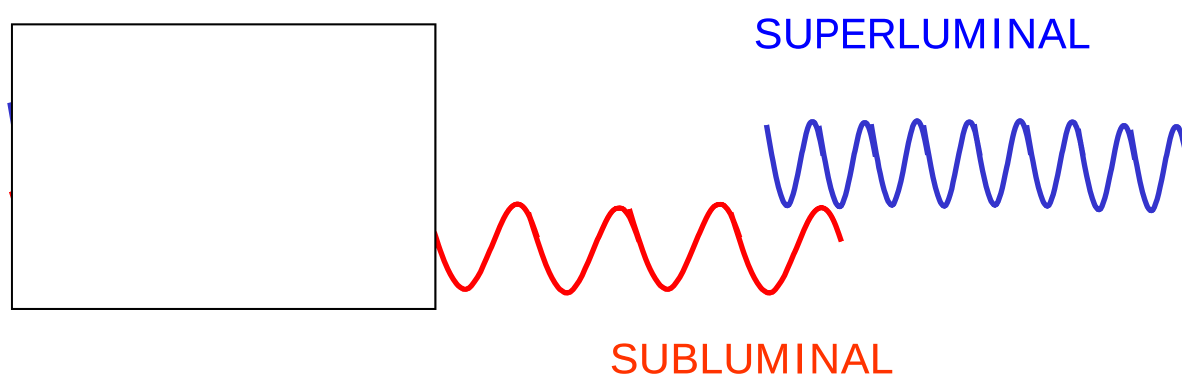
$$P_0 = 0.8\ \text{mW}$$

Objective

Finding other phenomena to control the change in the light propagation regimen in EDFA using CPO

First phenomenom

We control the transition from sub to superluminal propagation with solely changing the **modulation frequency** of the signal



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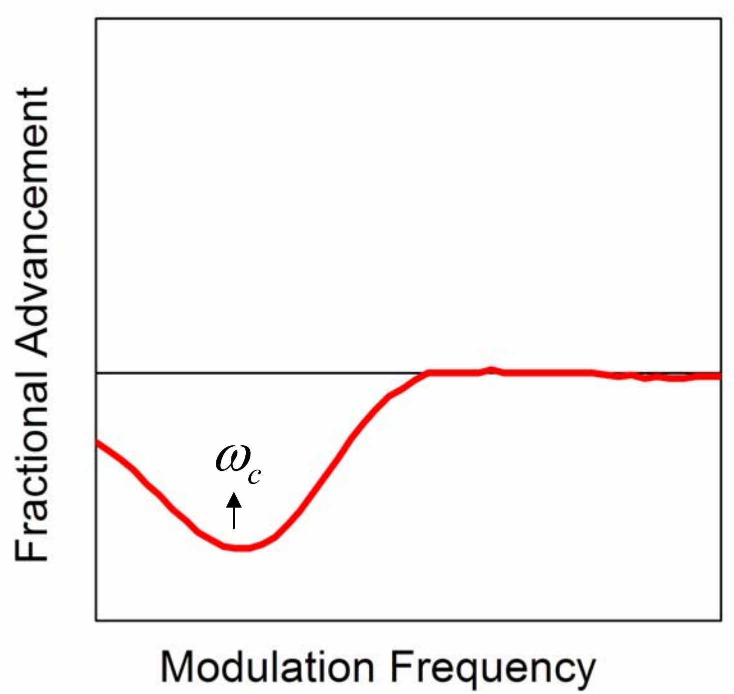
First phenomenom

Motivation: Bandwith broadening when increasing pump power

$$\omega_c = 1 + \hat{P}_0 + \hat{P}_p$$



No pump or low pump leves ➔ Large delays for low-frequency signals

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First phenomenom

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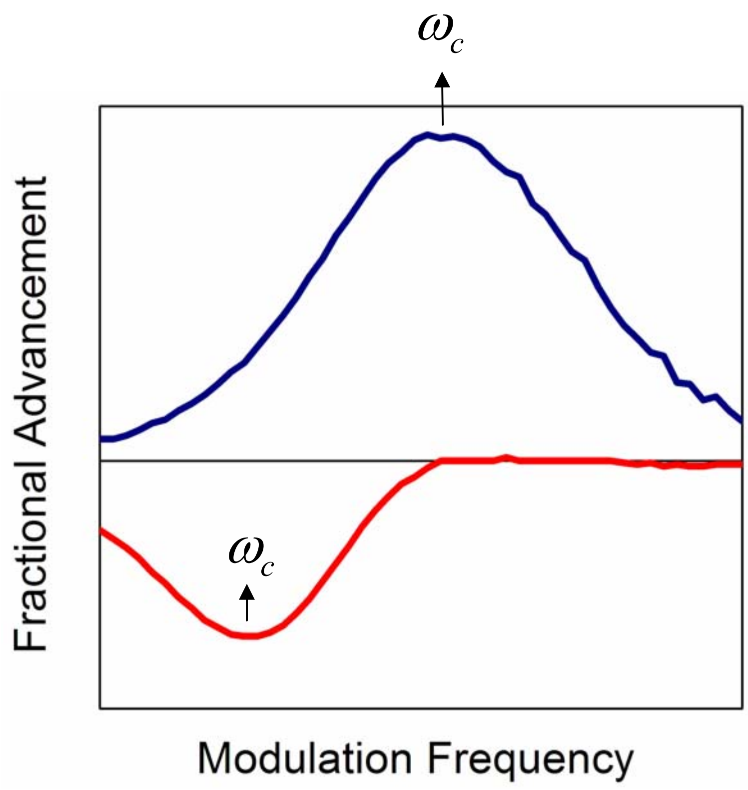
$$\omega_c = 1 + \hat{P}_0 + \hat{P}_p$$



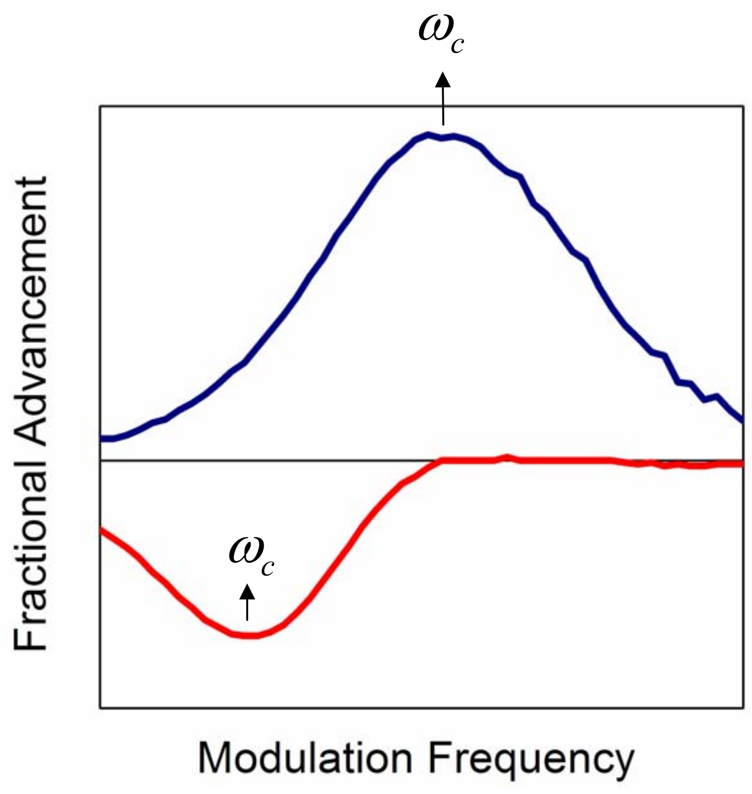
High pump levels ➔ Large advancement for high-frequency signals

No pump or low pump leves ➔ Large delays for low-frequency signals

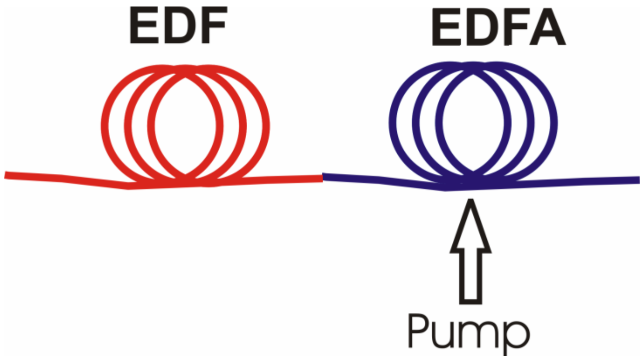
First phenomenom

Motivation: Bandwith broadening when increasing pump power

$$\omega_c = 1 + \hat{P}_0 + \hat{P}_p$$



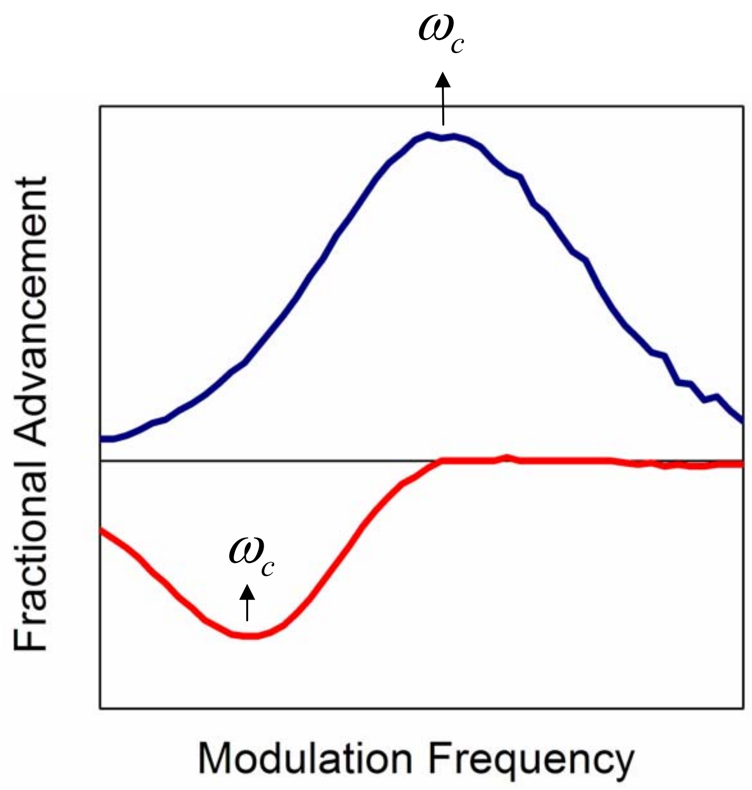
Combining these two behaviors in the same system ➔



First phenomenom

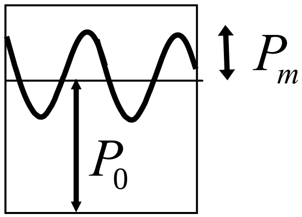
Motivation: Bandwith broadening when increasing pump power

$$\omega_c = 1 + \hat{P}_0 + \hat{P}_p$$



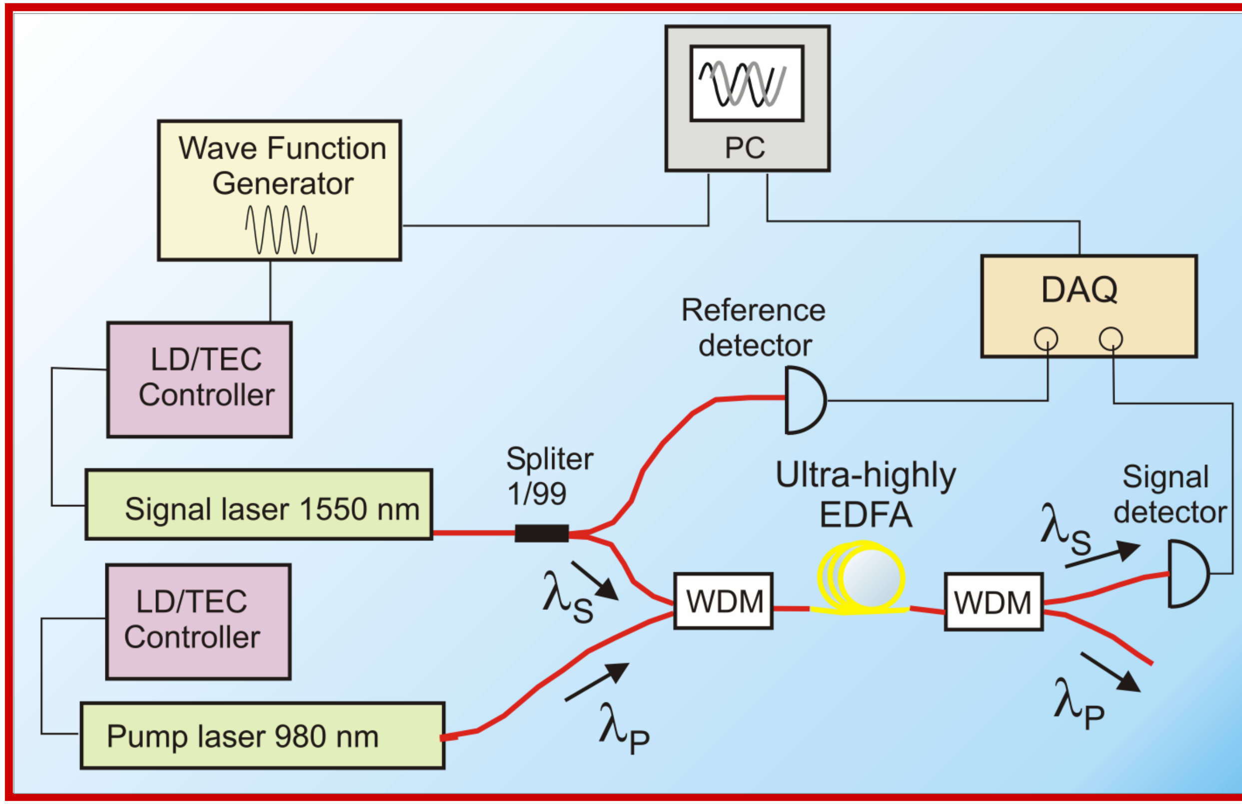
A more compact device using ultra-highly Er doped fiber amplifiers ➔ huge variation of gain profile along the fiber

Experimental setup I: 1550nm modulated signal with 980nm pump

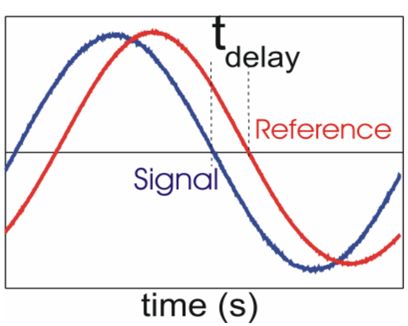


$$P_S = P_0 + P_m \cos(\omega_m t)$$

$$P_0 = 0.5\,\text{mW}$$
$$P_m = 0.5 P_0$$



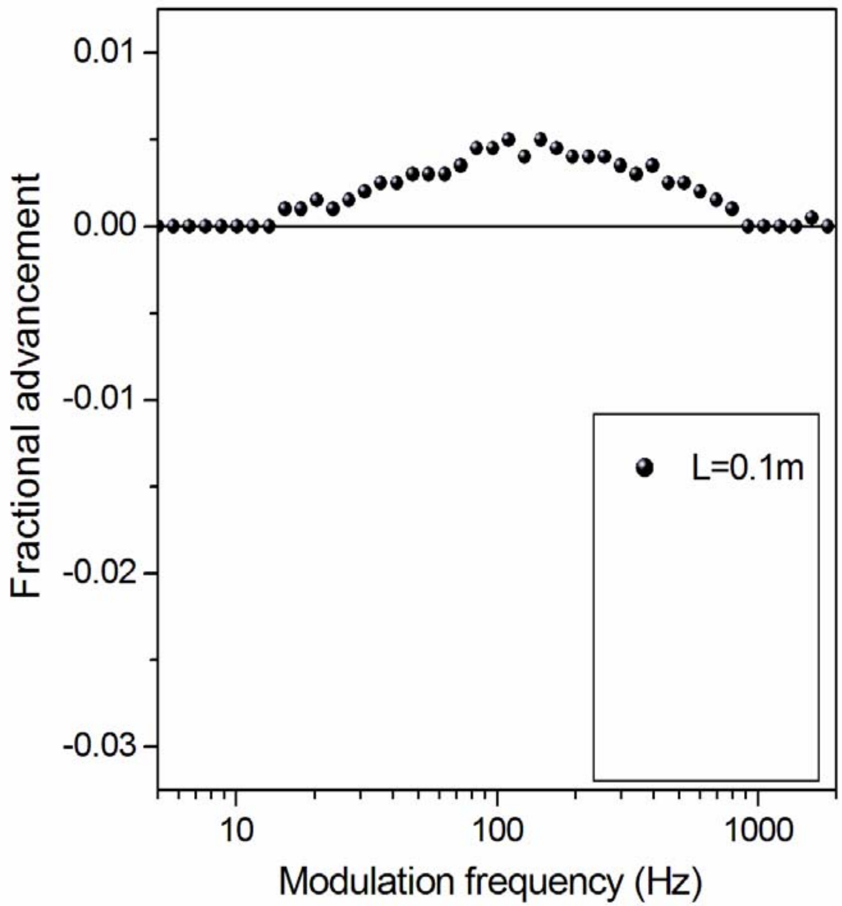
$$\rho = 6.3 - 8.7 \times 10^{25}\ \text{m}^{-3}$$



Fractional delay

$$F = \frac{\omega_m}{2\pi} t_{delay}$$

Results I: Fiber length



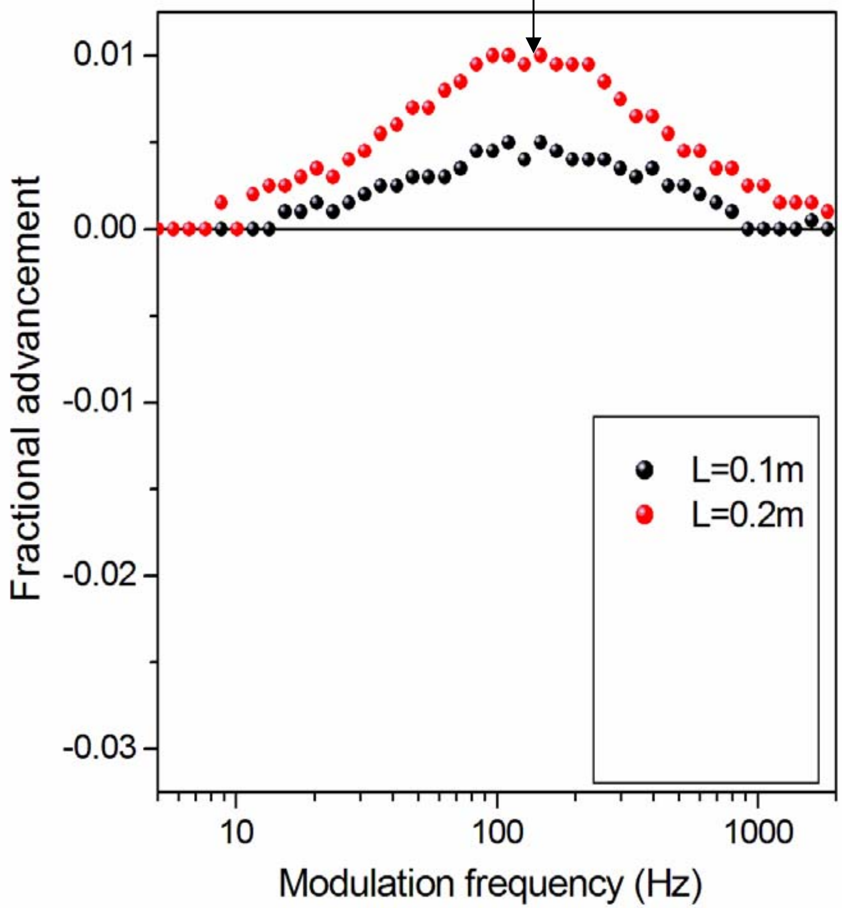
$P_p = 8\,\mathrm{mW}$

$\rho = 6.3\times 10^{25}\ \mathrm{m}^{-3}$

Er 80dB/m

Results I: Fiber length

$$\omega_c = 1 + \hat{P}_0 + \hat{P}_p$$



$$P_p = 8\ \text{mW}$$

$$\rho = 6.3 \times 10^{25}\ \text{m}^{-3}$$

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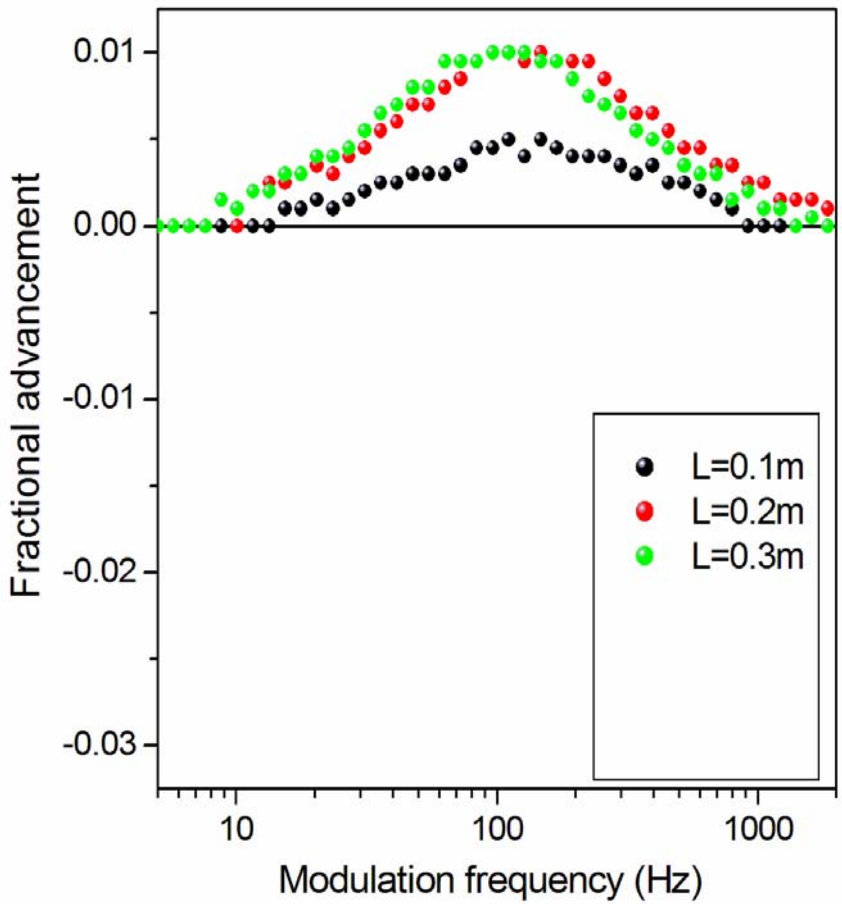
Results I: Fiber length



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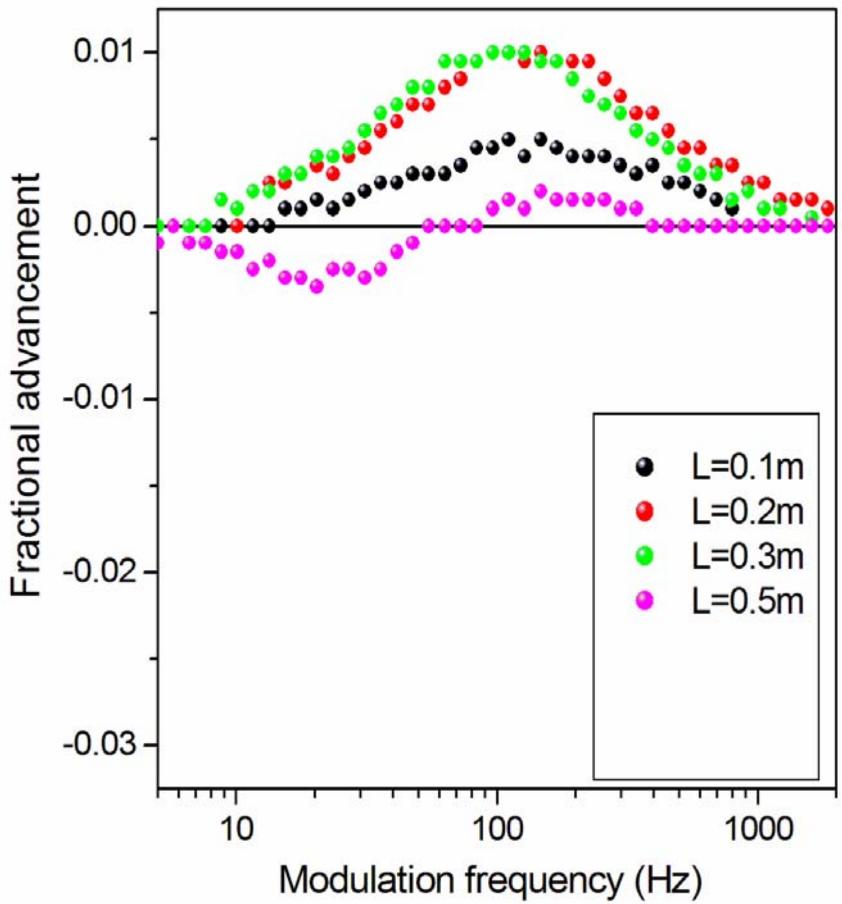

$P_p = 8\ \mathrm{mW}$

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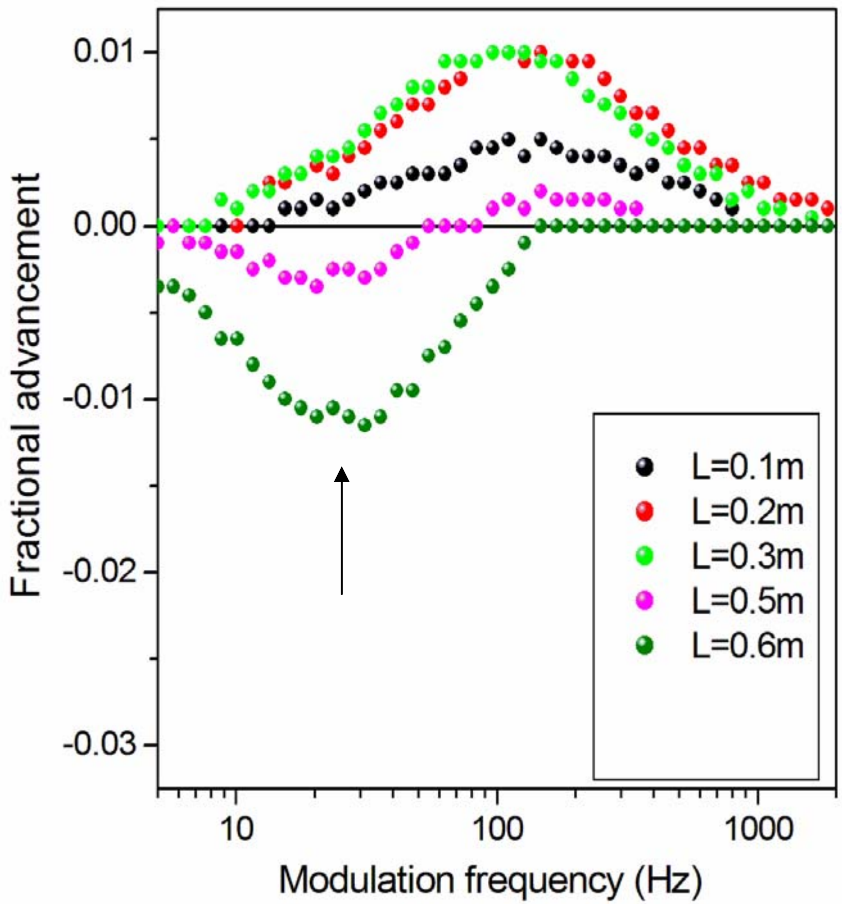
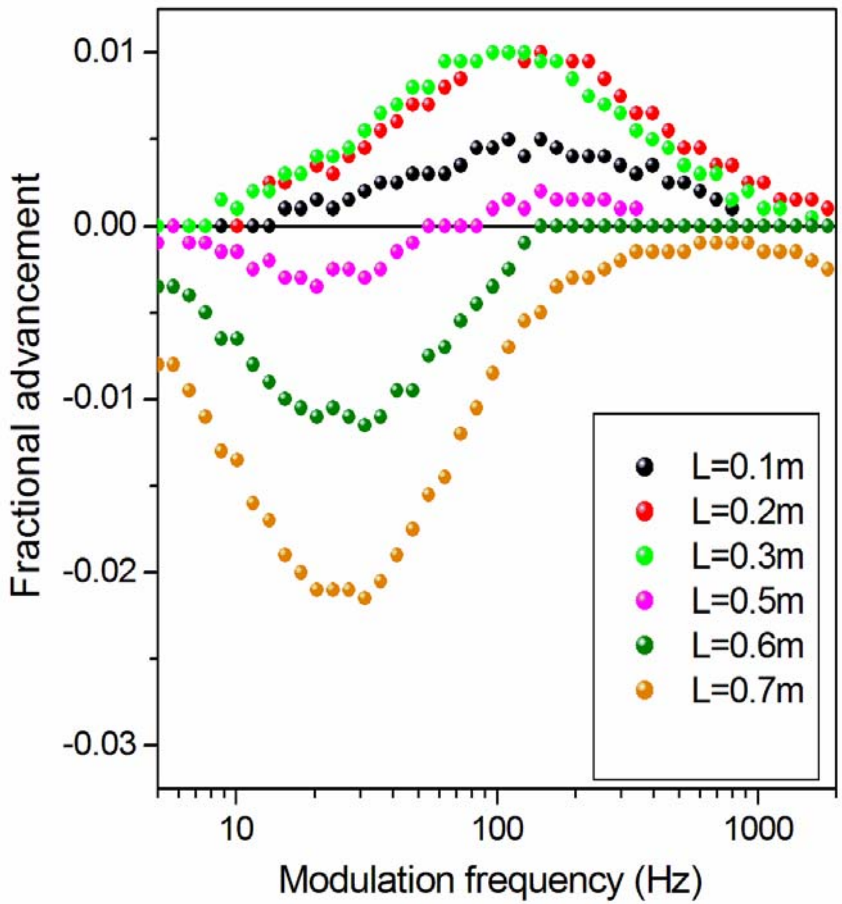
Results I: Fiber length



$$P_p = 8\,\mathrm{mW}$$

$$\rho = 6.3\times10^{25}\ \mathrm{m}^{-3}$$

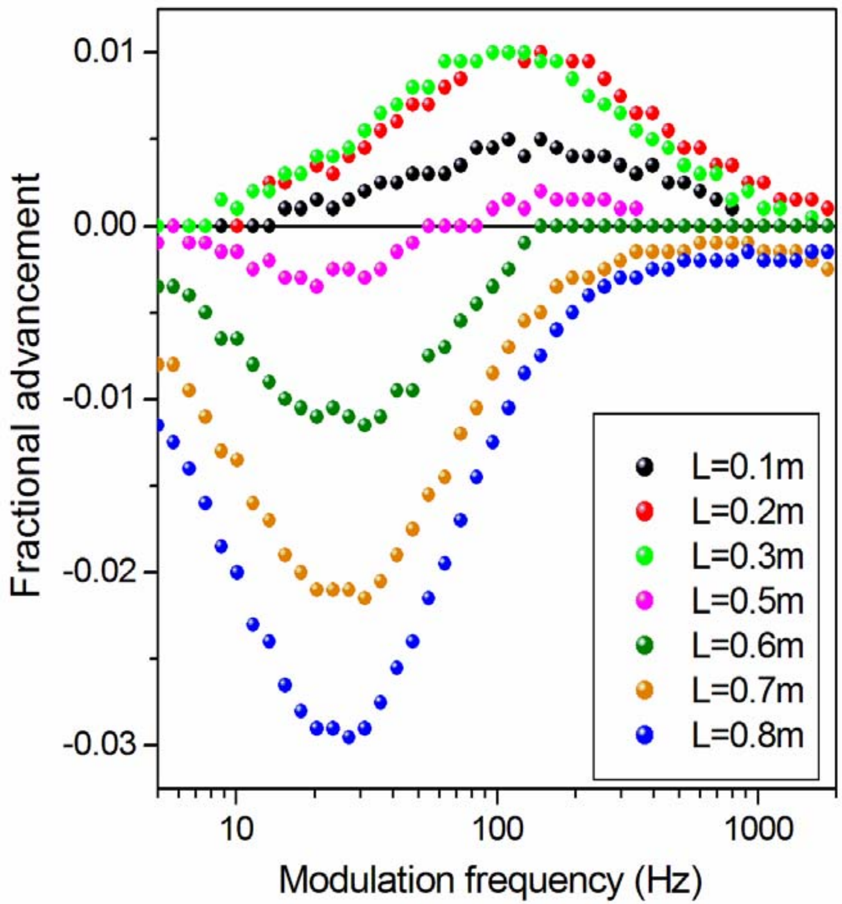
Results I: Fiber length



$P_p = 8\ \mathrm{mW}$

$\rho = 6.3 \times 10^{25}\ \mathrm{m}^{-3}$

Results I: Fiber length



$$P_p = 8\,\text{mW}$$

$$\rho = 6.3\times10^{25}\ \text{m}^{-3}$$

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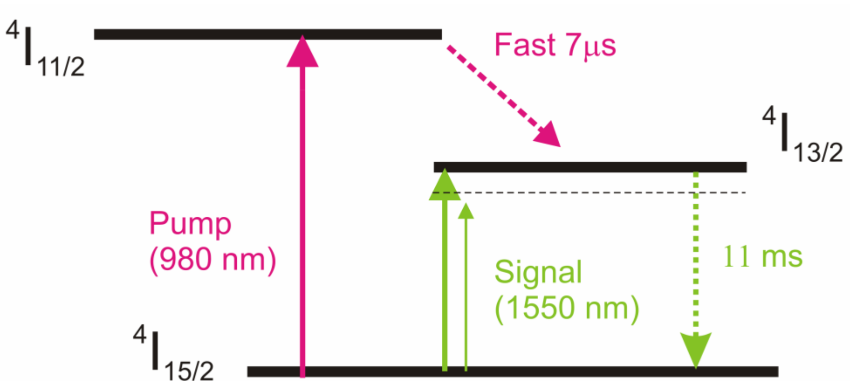
Results I: Simulations using rate equations



Signal	$P_S = P_0 + P_m \cos(\omega_m t)$
Pump	P_p
Population oscillation	$n_1 = n_1^{st} + n_1^{c} \cos(\omega_m t) + n_1^{s} \sin(\omega_m t)$

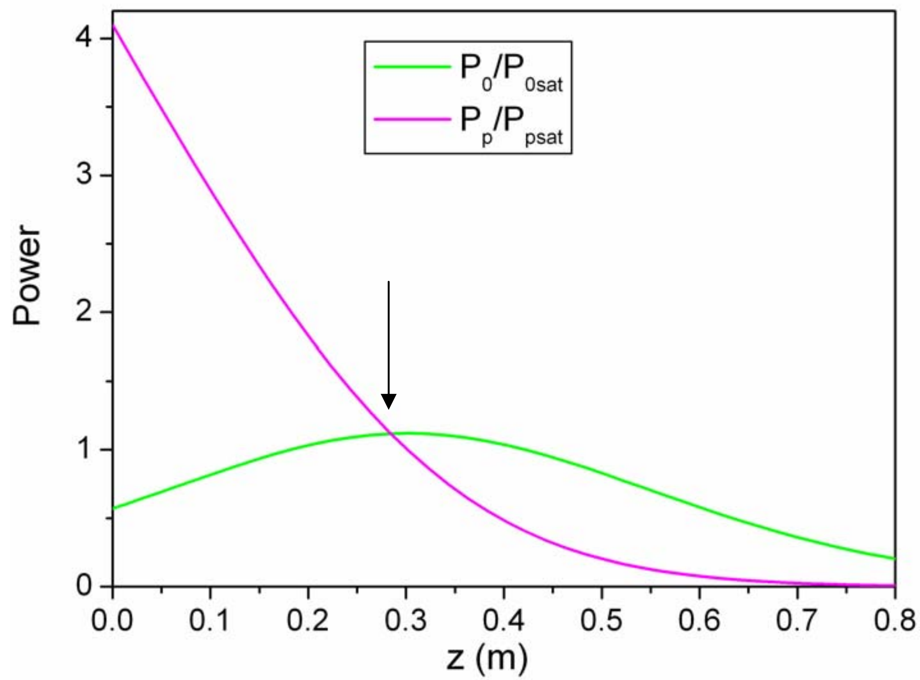
$$\omega_c = 1 + \hat{P}_0 + \hat{P}_p$$

Propagation equations

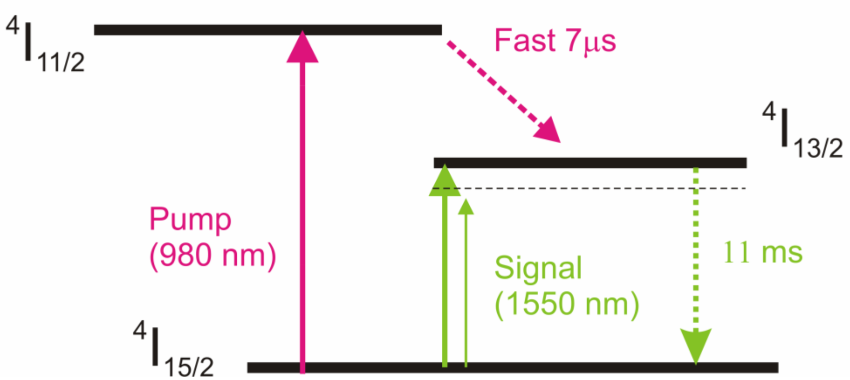
$$\frac{\partial \hat{P}_0}{\partial z'} = \alpha_s \frac{(\hat{P}_p - 1)\hat{P}_0}{1 + \hat{P}_0 + \hat{P}_p}$$

$$\frac{\partial \hat{P}_p}{\partial z'} = -\alpha_p \frac{\left(1 + \hat{P}_0 / 2\right)\hat{P}_p}{1 + \hat{P}_0 + \hat{P}_p}$$

$$\frac{\partial \phi}{\partial z'} = \alpha_s \frac{(\hat{P}_p - 1)\hat{P}_0}{\omega_c} \frac{\omega_m \tau}{\omega_c^2 + \omega_m^2}$$



Results I: Simulations using rate equations



Signal $P_S = P_0 + P_m \cos(\omega_m t)$

Pump P_p

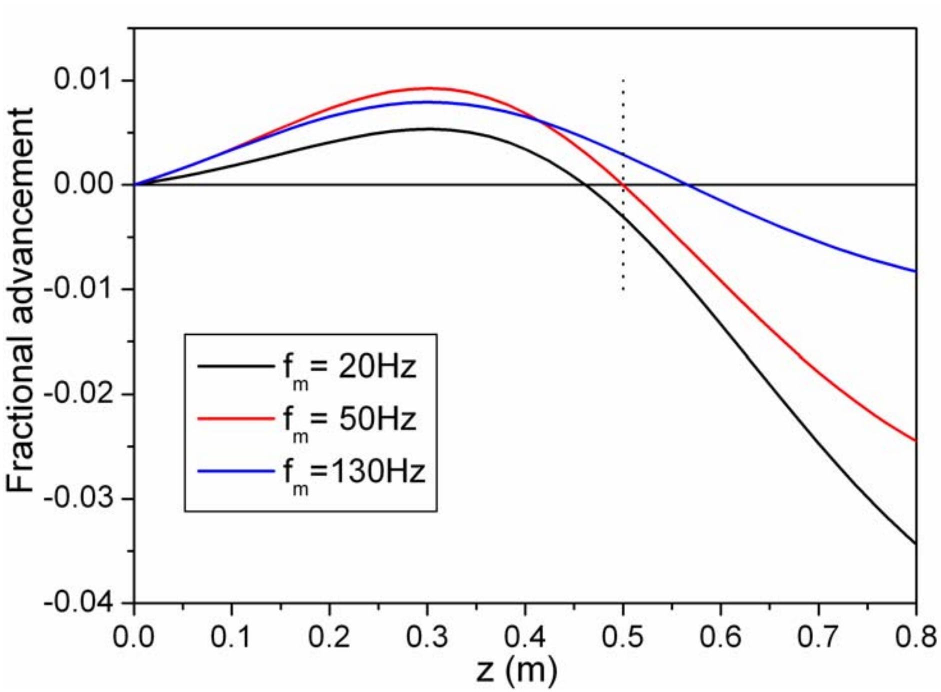
Population oscillation $n_1 = n_1^{st} + n_1^c \cos(\omega_m t) + n_1^s \sin(\omega_m t)$

Propagation equations

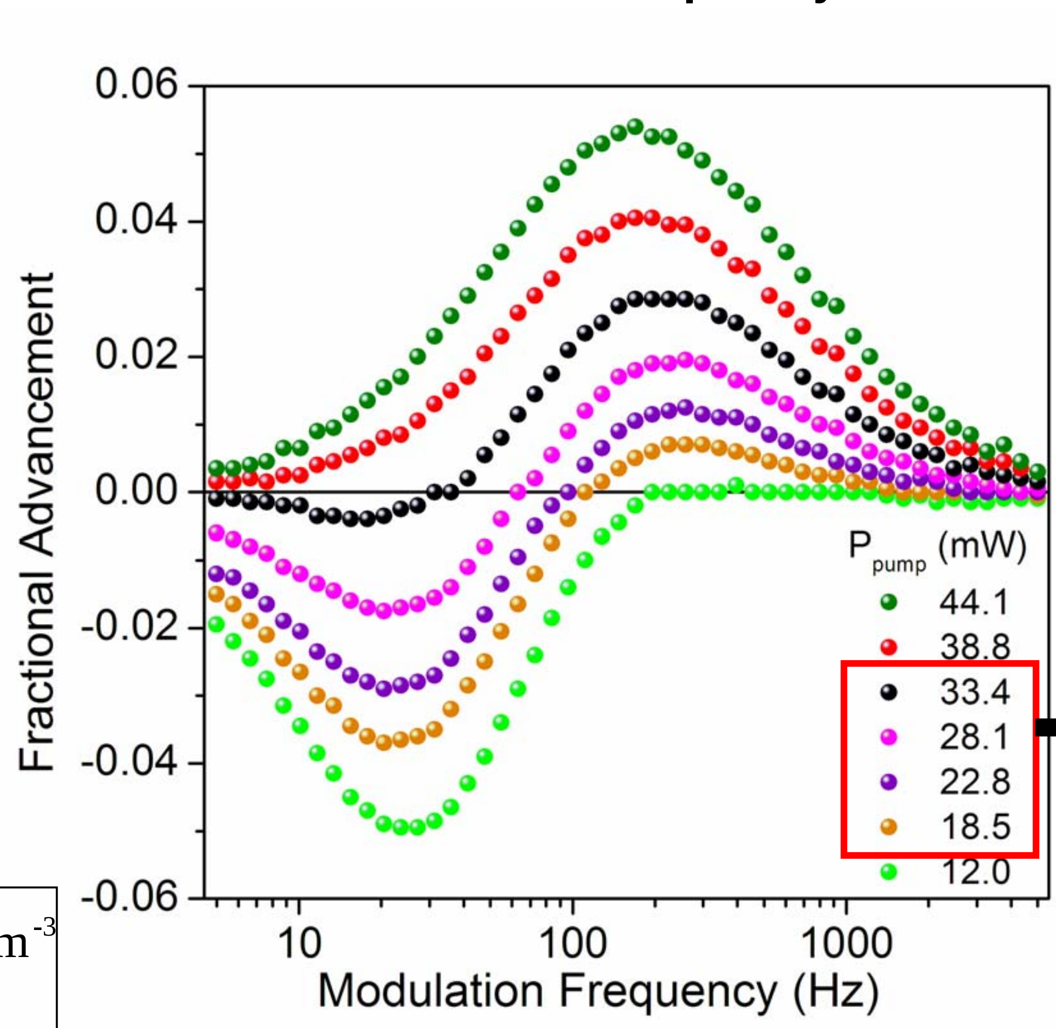
$$\frac{\partial \hat{P}_0}{\partial z'} = \alpha_s \frac{(\hat{P}_p - 1)\hat{P}_0}{1 + \hat{P}_0 + \hat{P}_p}$$

$$\frac{\partial \hat{P}_p}{\partial z'} = -\alpha_p \frac{\left(1 + \hat{P}_0 / 2\right)\hat{P}_p}{1 + \hat{P}_0 + \hat{P}_p}$$

$$\frac{\partial \phi}{\partial z'} = \alpha_s \frac{(\hat{P}_p - 1)\hat{P}_0}{\omega_c} \frac{\omega_m \tau}{\omega_c^2 + \omega_m^2}$$



Results I: Change in the propagation regime induced by the modulation frequency



net delay or advancement is obtained depending on the modulation frequency

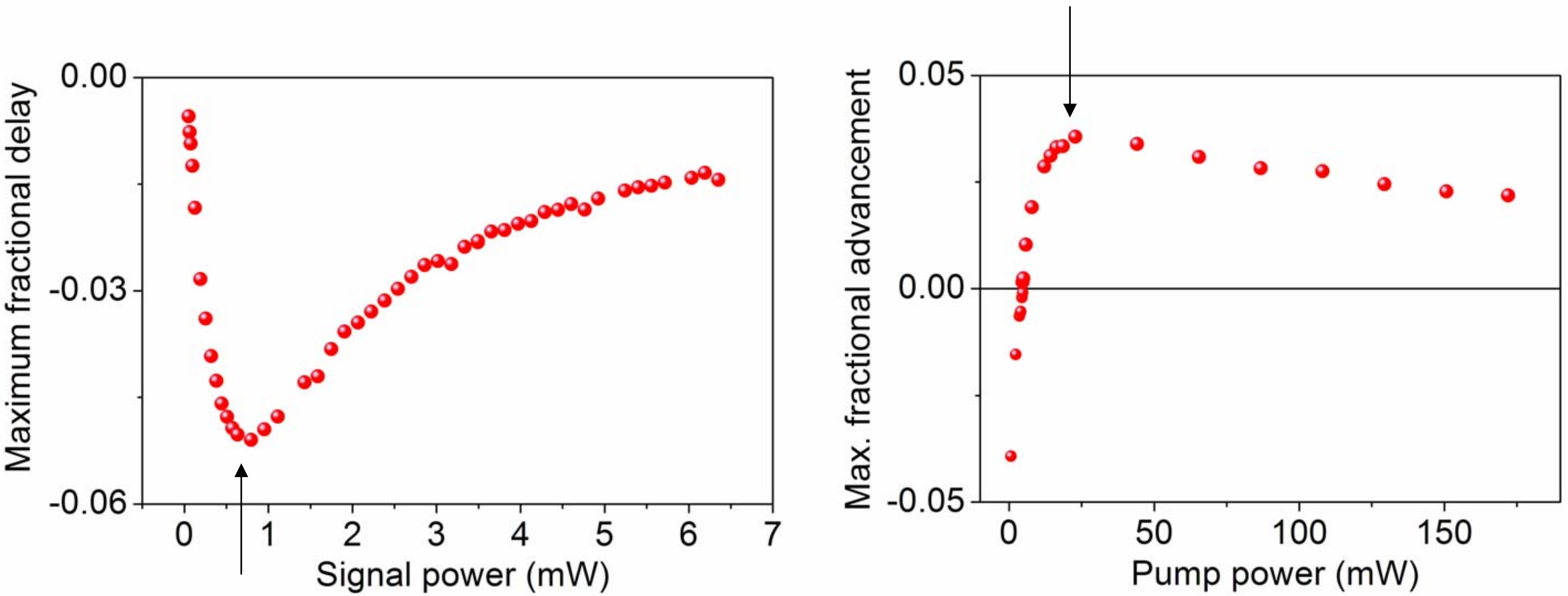
$$\rho = 6.3 \times 10^{25}\ \mathrm{m}^{-3}$$
$$L = 1\ \mathrm{m}$$

Er 80dB/m

Melle et al, Opt. Lett. **33**, 827 (2008)

Second phenomenom

Motivation: Delay and advancement saturation with signal and pump power



Er 20dB/m

DELAY/ADV LIMIT

Melle et al., Opt. Commun. **279**, 53 (2007); Opt. Lett. **33**, 827 (2008)
Zhang et al., Phys. Lett. A **372,** 2724 (2008)

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Objective

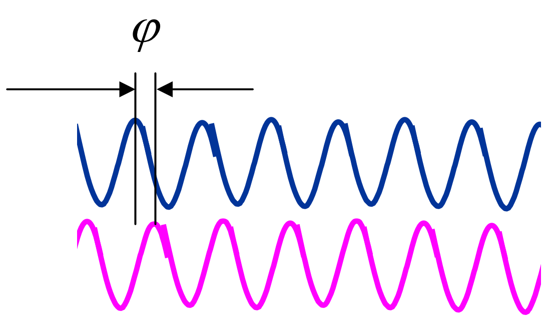
- **Finding other phenomena to control the change in the light propagation regimen in EDFA using CPO**

- **Enhance the maximum fractional delay and advancement to avoid the previous limitation**

Second phenomenom

We force the population oscillations by modulating the pump at the same frequency of the signal ➔

we control the velocity of propagation with the **relative phase** between the modulated pump and the modulated signal.



Signal $$P_S = P_{0s} + P_{ms}\cos(\omega_m t)$$

Pump $$P_p = P_{0p} + P_{mp}\cos(\omega_m t - \varphi)$$

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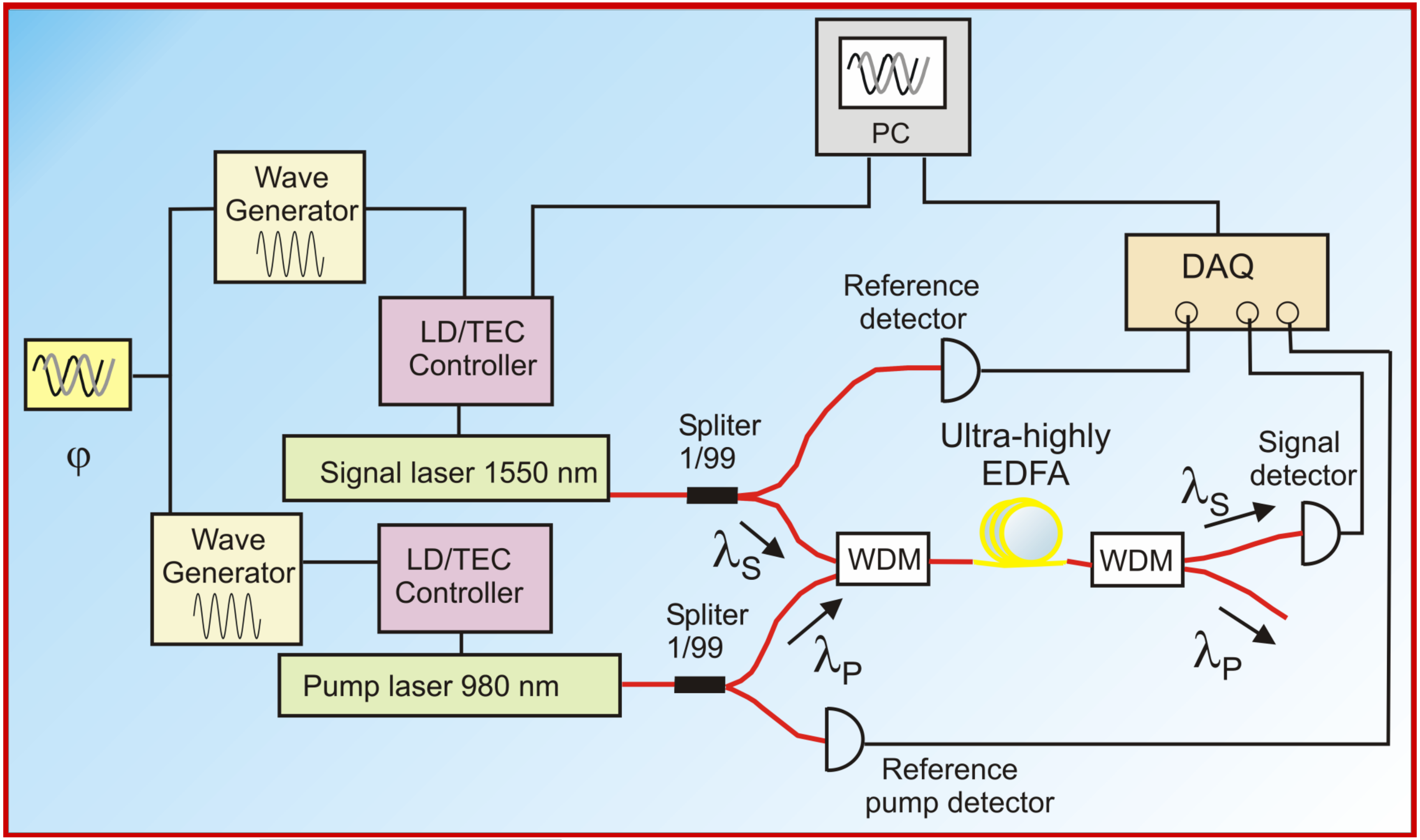
Experimental setup II: 1550nm-modulated signal with 980nm-modulated pump



$$P_s^{sat} = 0.35\ \mathrm{mW}$$
$$P_p^{sat} = 1.27\ \mathrm{mW}$$

$$L = 0.1\ \mathrm{m}$$
$$\rho = 6.3 \times 10^{25}\ \mathrm{m}^{-3}$$

Er 80dB/m

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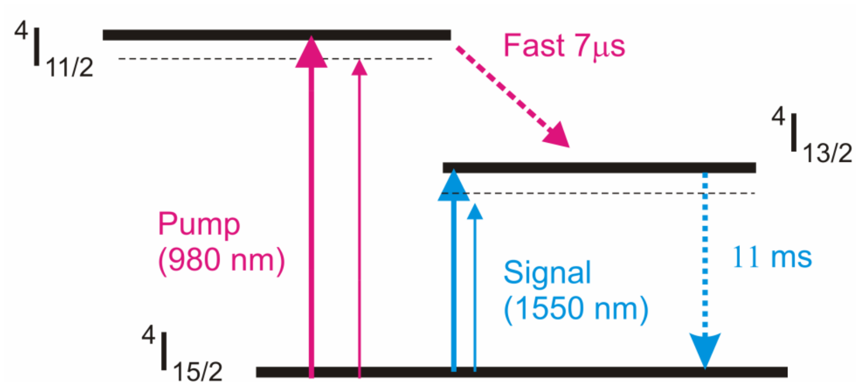
Results II: Simulations using rate equations



Signal	$P_S = P_{0s} + P_{ms}\cos(\omega_m t)$
Pump	$P_p = P_{0p} + P_{mp}\cos(\omega_m t - \varphi)$
Population oscillation	$n_1 = n_1^{st} + n_1^c \cos(\omega_m t) + n_1^s \sin(\omega_m t)$

$$\omega_c = 1 + \hat{P}_{0s} + \hat{P}_{0p}$$

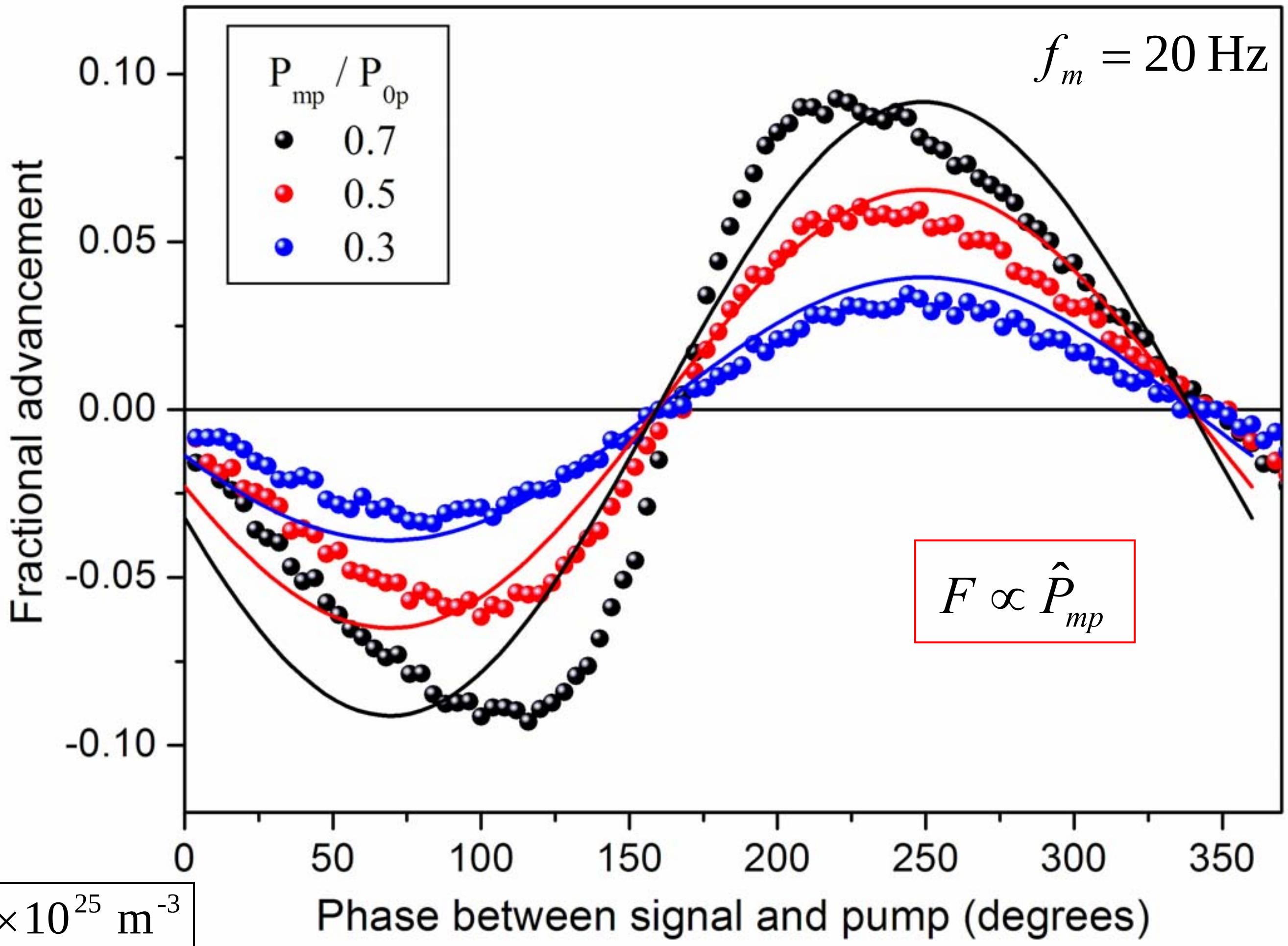
Short lengths ➔
Non depleted solution

$$F = \frac{\alpha_s}{2\pi}\frac{\hat{P}_{0s}}{\omega_c(\omega_c^2+\omega_m^2)}\left[\omega_m(\hat{P}_{0p}-1) - \frac{\hat{P}_{mp}}{\hat{P}_{ms}}(\hat{P}_{0s}+2)\left[\omega_c \sin\varphi + \omega_m \cos\varphi\right]\right]$$

New term

FRACTIONAL ENHANCEMENT by increasing $\hat{P}_{mp}$ or decreasing $\hat{P}_{ms}$

Results II: Pump modulation amplitude



$P_{os} = 0.65$ mW

$P_{ms} / P_{0s} = 0.5$

$P_{op} = 2$ mW

Maximum fractional delay increases linearly with pump modulation

$\rho = 6.3 \times 10^{25}\ \text{m}^{-3}$

$L = 0.1\ \text{m}$

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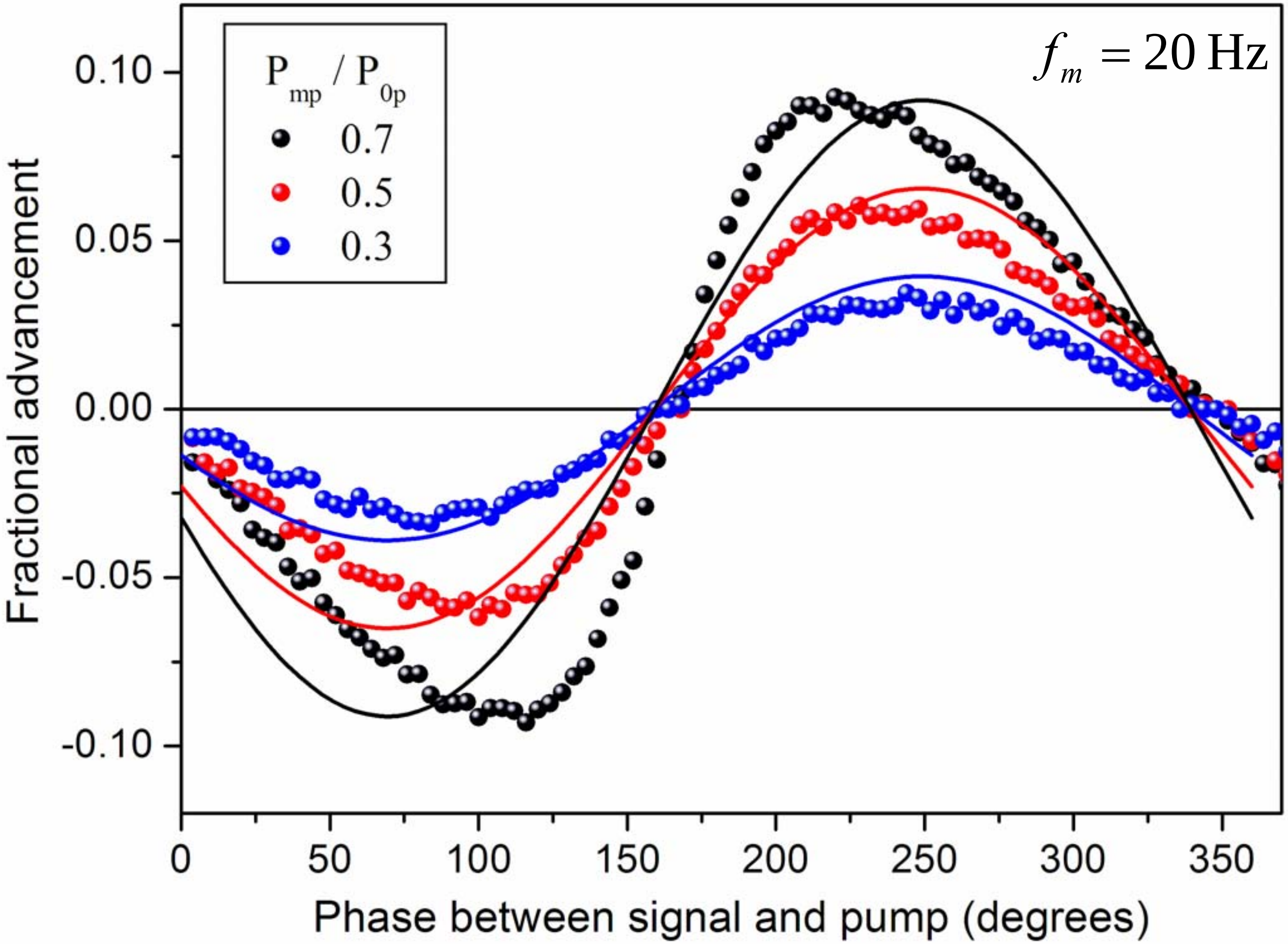
Results II: Pump modulation amplitude

$$P_{mp} = 0 \Rightarrow F \sim +\ 0.001$$ → **Advancement two orders of magnitude larger!**



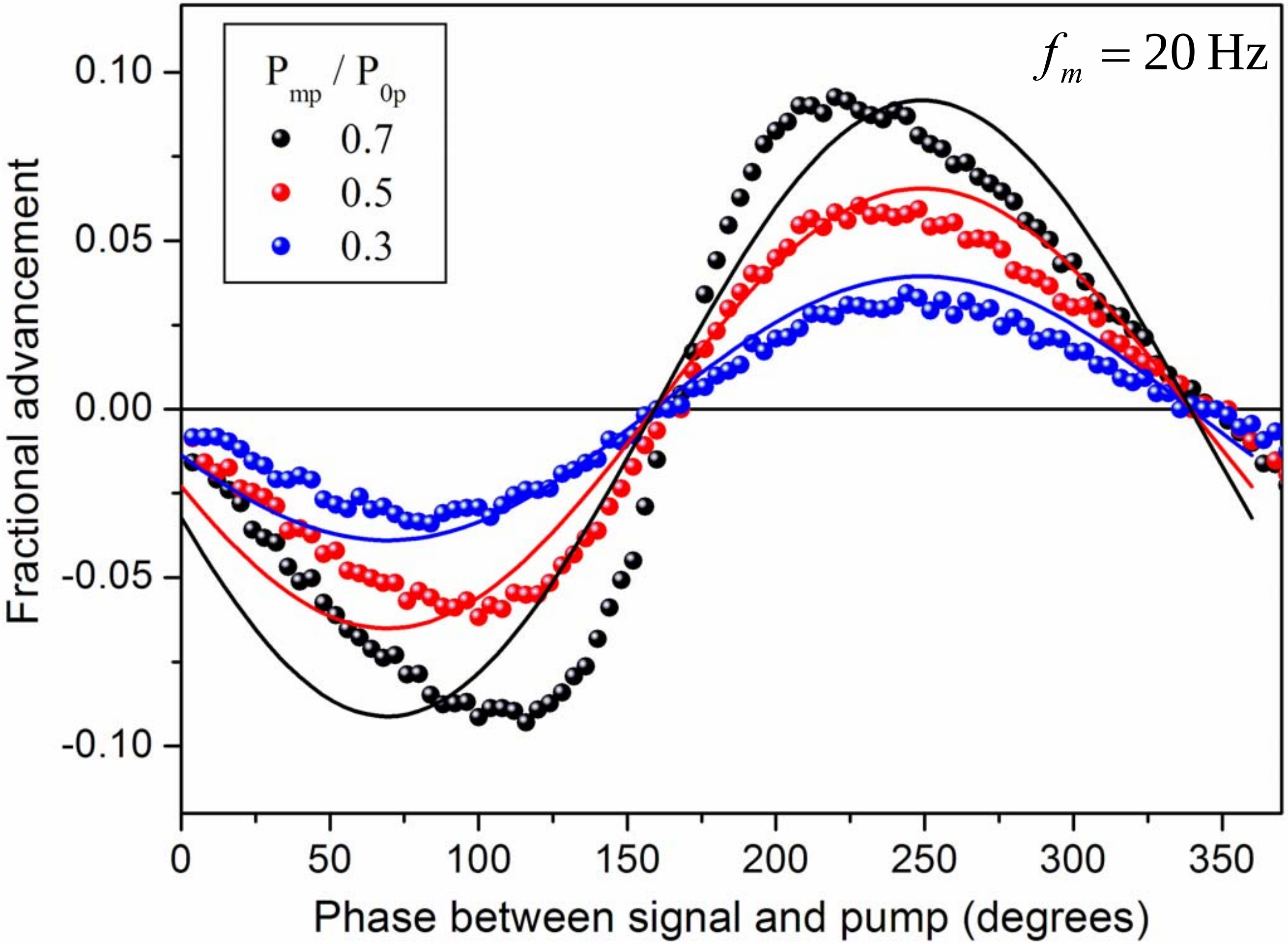
$P_{os} = 0.65$ mW

$P_{ms} / P_{0s} = 0.5$

$P_{op} = 2$ mW

Results II: Pump modulation amplitude

$$P_{0p} = 0 \Rightarrow F \sim -\ 0.01$$ → **Delay one order of magnitude larger!**



$P_{os} = 0.65$ mW

$P_{ms} / P_{0s} = 0.5$

$P_{op} = 2$ mW

Results II: Pump modulation amplitude

$$\rho = 6.3\times 10^{25}\ \mathrm{m}^{-3}$$
$$L = 0.1\,\mathrm{m}$$

$$f_m = 20\ \mathrm{Hz}\ \text{ so that } f_m < \frac{\omega_c}{2\pi}$$

No PUMP

$$P_{os} = 0.65\ \mathrm{mW}$$
$$P_{ms}/P_{0s} = 0.5$$

$$F_{MAX} \sim -\ 0.01$$

DC PUMP above threshold

$$P_{os} = 0.65\ \mathrm{mW}$$
$$P_{ms}/P_{0s} = 0.5$$
$$P_{op} = 2\ \mathrm{mW}$$

$$F_{MAX} \sim +\ 0.001$$

Optimum DC PUMP

$$P_{os} = 0.65\ \mathrm{mW}$$
$$P_{ms}/P_{0s} = 0.5$$
$$P_{op} = 30\ \mathrm{mW}$$

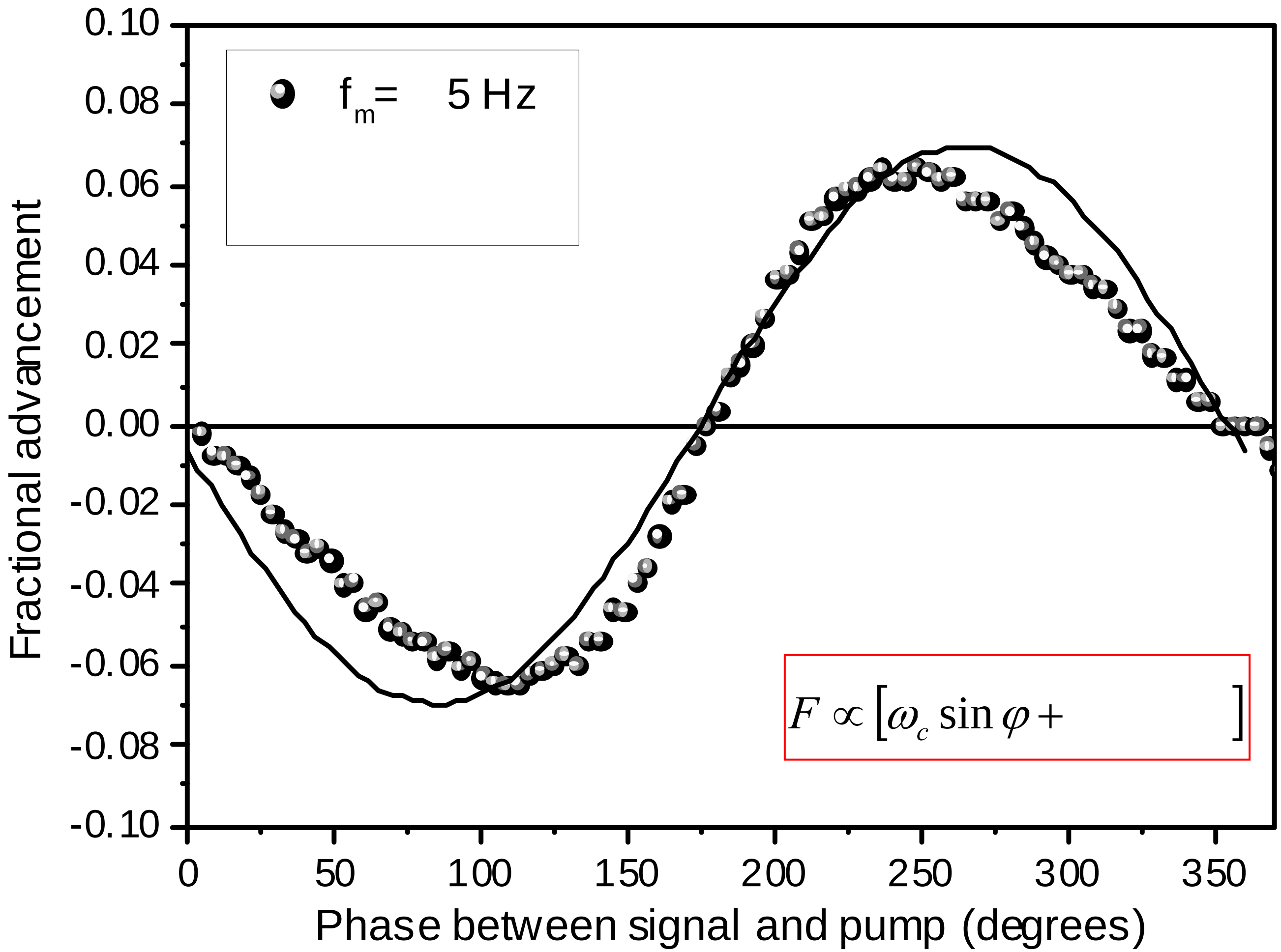
$$F_{MAX} \sim +\ 0.0025$$

Modulated PUMP

$$P_{os} = 0.65\ \mathrm{mW}$$
$$P_{ms}/P_{0s} = 0.5$$
$$P_{op} = 2\ \mathrm{mW}$$
$$P_{mp}/P_{0p} = 0.7$$

$$F_{MAX} \sim \pm\ 0.1$$

Results II: Modulation frequency



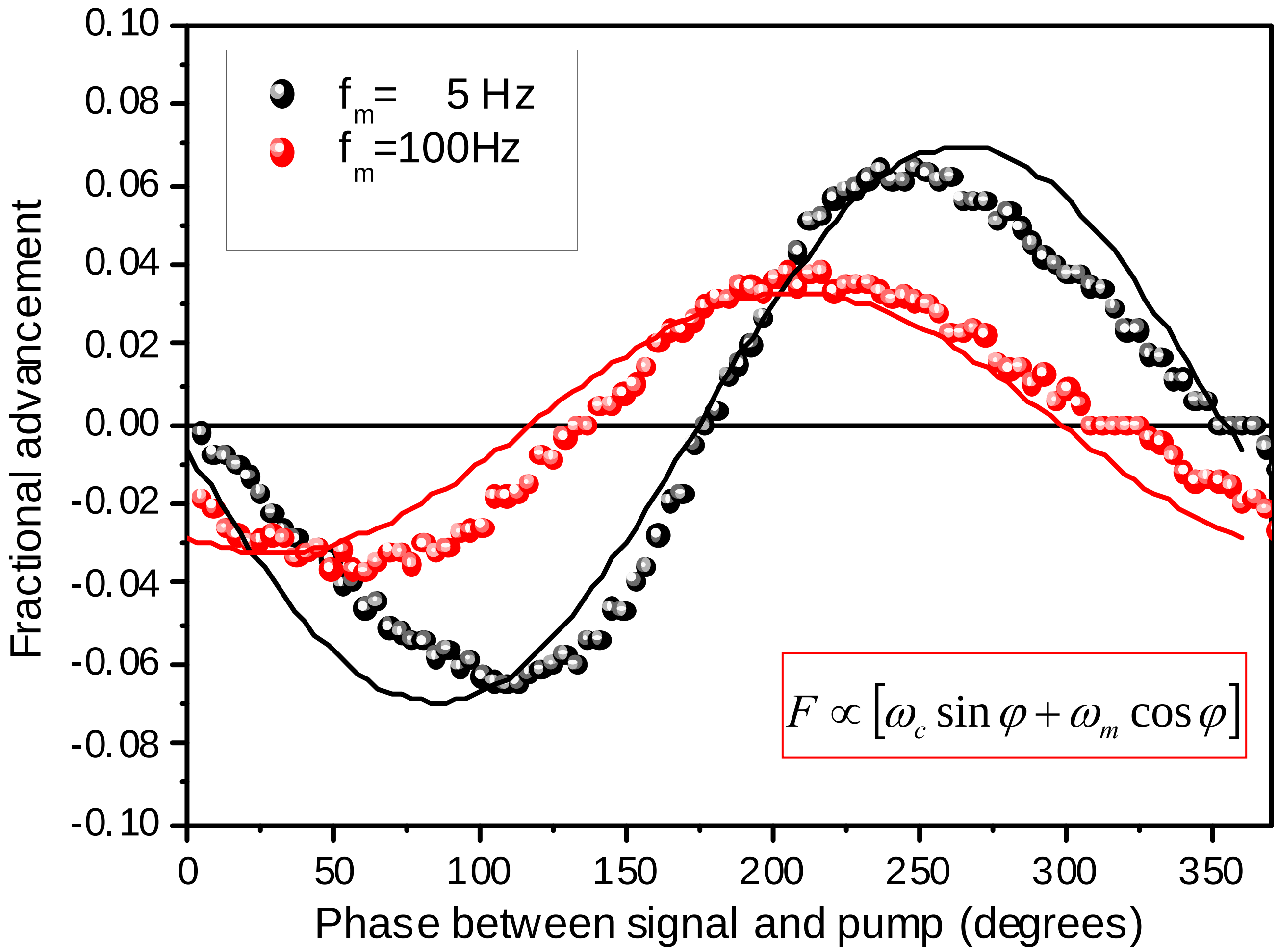
$P_{os} = 0.65$ mW

$P_{ms} / P_{0s} = 0.5$

$P_{op} = 2$ mW

$P_{mp} / P_{0p} = 0.5$

Results II: Modulation frequency



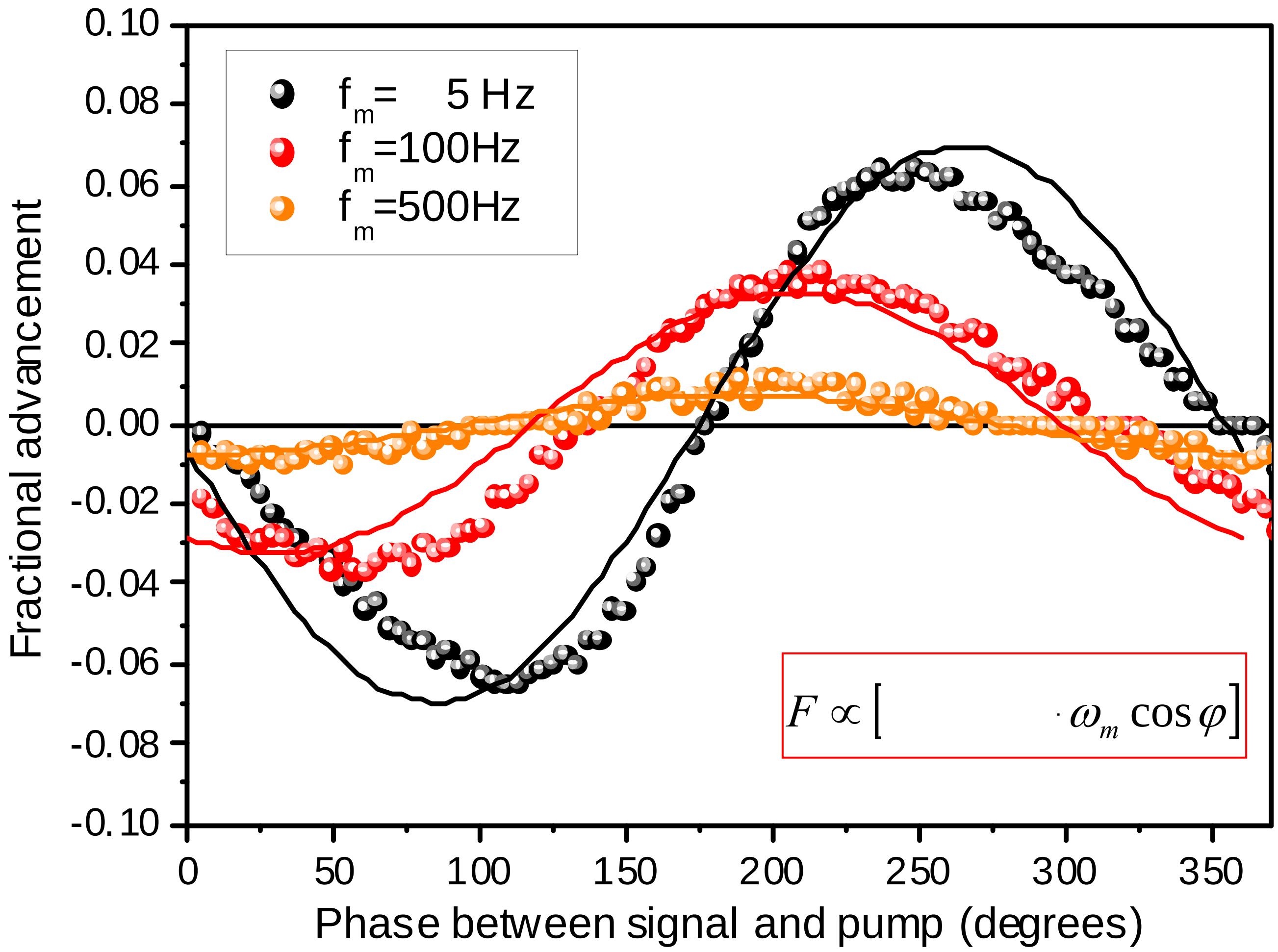
$P_{os} = 0.65$ mW

$P_{ms} / P_{0s} = 0.5$

$P_{op} = 2$ mW

$P_{mp} / P_{0p} = 0.5$

Results II: Modulation frequency



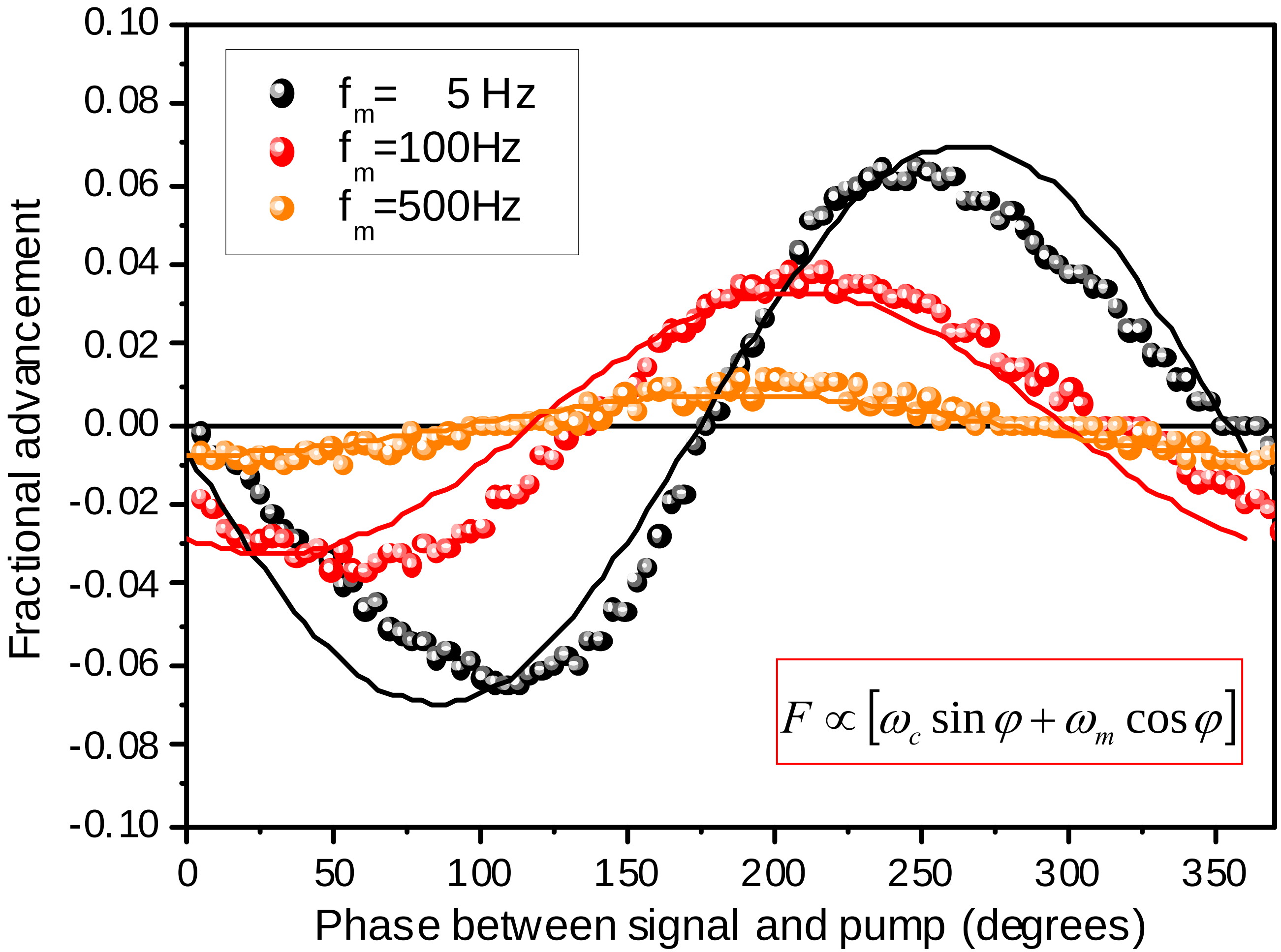
$P_{os} = 0.65$ mW

$P_{ms} / P_{0s} = 0.5$

$P_{op} = 2$ mW

$P_{mp} / P_{0p} = 0.5$

Results II: Modulation frequency



$P_{os} = 0.65$ mW

$P_{ms} / P_{0s} = 0.5$

$P_{op} = 2$ mW

$P_{mp} / P_{0p} = 0.5$

The optimum relative phase shifts with the modulation frequency

Conclusions

We have propose two different processes for controlling the propagation velocity of light enabled by CPO:

By changing the modulation frequency

For each fiber length there is a **range of pump powers** for which a net delay or advancement is obtained depending on the value of the modulation frequency.

By forcing the population oscillations with a modulated pump

We **enhance** the fractional delay and advancement **more than an order of magnitude** by modulating the pump power to increase the oscillations of the ground level population.

The **relative phase** between the pump and the modulated signal is an **optimum parameter** to control the propagation regime.

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