Title: Towards the Production of Entangled Photon Pairs in Optical Fiber via Four-Wave Mixing

Date: Jun 02, 2007 03:00 PM

URL: http://pirsa.org/07060012

Abstract: Previous experiments on the production of entangled photon pairs directly in optical fiber via four-wave mixing (FWM) have used a single pump laser and produced signal and idler photons with similar wavelengths. We will present the first results of our investigation into the production of widely separated entangled photon pairs via FWM in optical fiber using multiple pump lasers also at widely separated wavelengths. This source will have important applications in quantum cryptography and computation. As fiber optic and free space quantum communication networks require photons at different wavelengths (1550 nm and around 800 respectively) this source will make hybrid quantum cryptography networks achievable and could also be used as a heralded optical fiber source of single photons.

Towards the Production of Entangled Photon Pairs in Optical Fiber via Four Wave Mixing

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Institute for Quantum Information Science at the University of Calgary

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Motivation

- Past FWM Experiments
  - Photon Pairs | Pump Wavelength

Photon Pairs		Pump Wavelength
1547 & 1525 nm	←	1537 nm P. Kumar et al. PRL 94, 053601
900 & 583 nm	←	708 nm J. G. Rarity et al. quant-ph/0611232

Motivation

Our Goal: Produce Entangled Photons at widely separated wavelengths

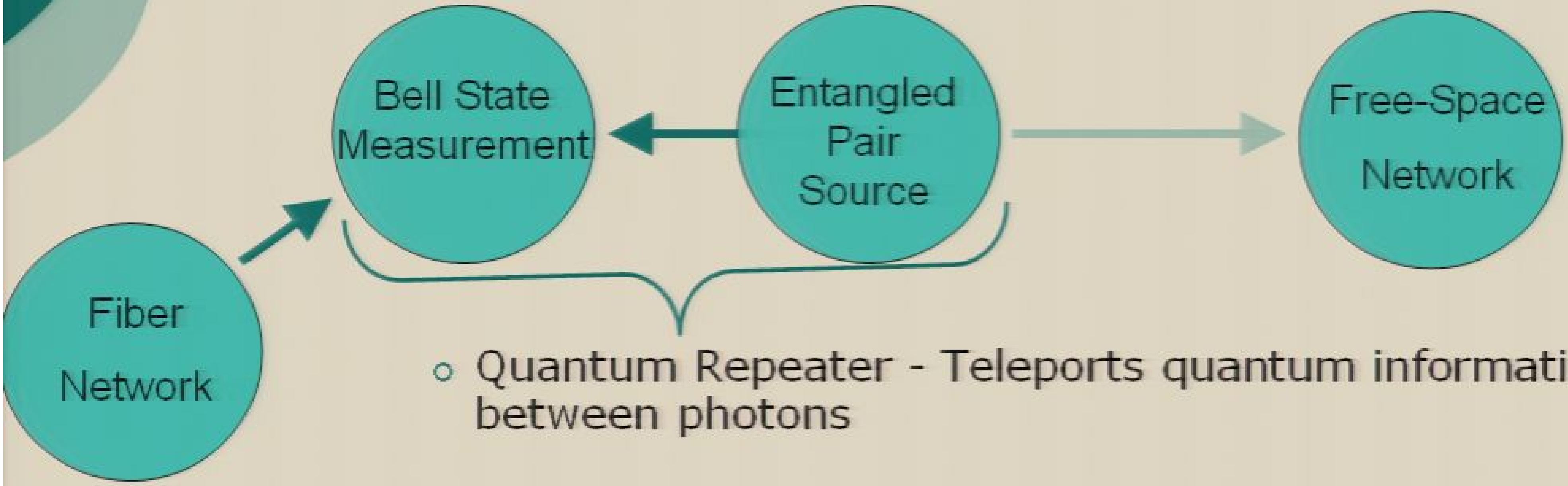
1550 nm - Third Telecom Window

↕

800 nm - Low atmospheric absportion

Motivation – Why large Separation?

- Enabling Quantum Repeaters
  - Link Fiber - Free-Space networks



Bell State Measurement

Entangled Pair Source

Free-Space Network

Fiber Network

- Quantum Repeater - Teleports quantum information between photons

- Heralding Fiber Single Photon Source
  - as there are fast, quiet, efficient detectors for 800 nm

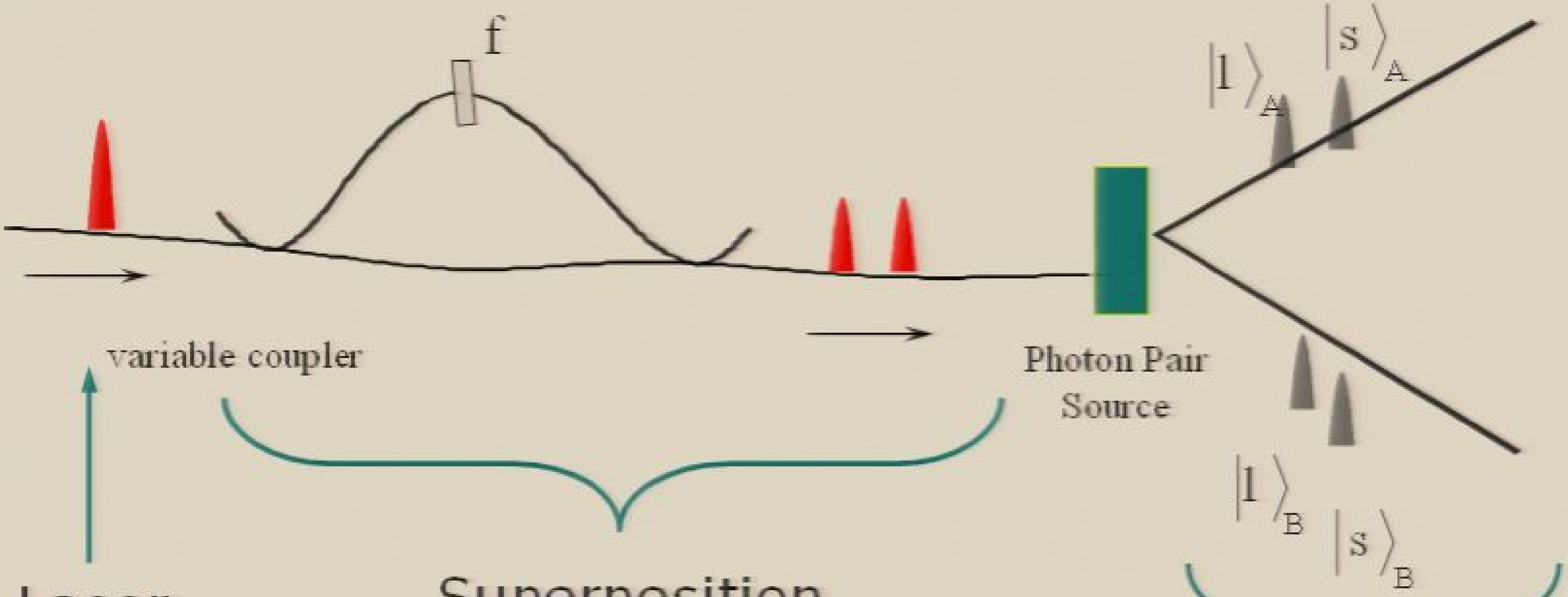
Motivation – Why Optical Fiber?

- Optical Fibers are robust, compact, and simple to align – Making for a simple quantum repeater

- Four Wave Mixing gives us an extra handle
  - as FWM experiments can be done with two pumps, one can play with parameters such as coherence lengths to produce the complete range of states from pure entanglement to completely mixed states

Producing Entanglement

- Time-Bin Entanglement



Laser Pulse

Superposition

$$|l\rangle + e^{i\phi}|s\rangle$$

Entanglement

$$|l\rangle_A|l\rangle_B + e^{i\phi}|s\rangle_A|s\rangle_B$$

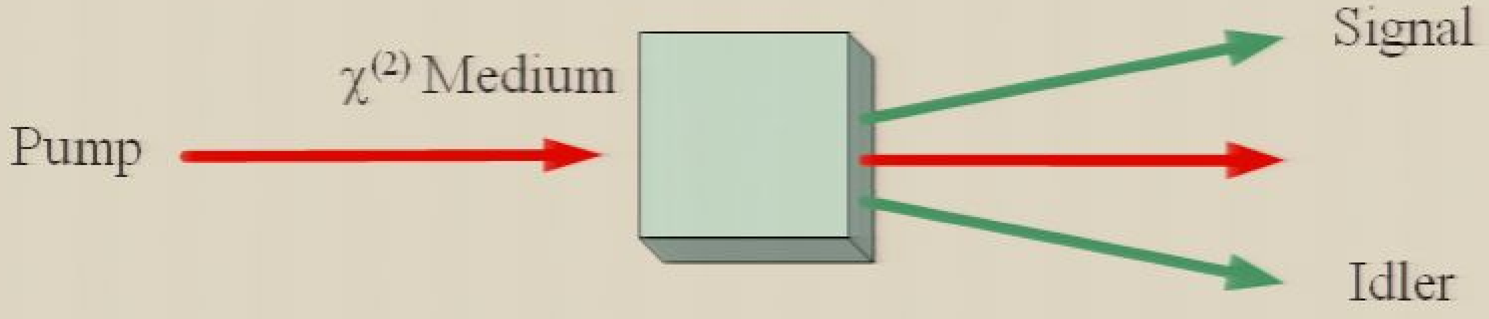
Producing Photon Pairs

- Non-Linear Optics

$$\mathbf{P} = \varepsilon_0(\chi^{(1)}\mathbf{E} + \chi^{(2)}\mathbf{EE} + \chi^{(3)}\mathbf{EEE} + \ldots)$$

- Second Order Effects:
  - Parametric down-conversion in nonlinear crystals

$$\omega_1 \rightarrow \omega_2 + \omega_3 \qquad \mathbf{k}_1 \rightarrow \mathbf{k}_2 + \mathbf{k}_3 \qquad \mathbf{k}_i = \frac{n_i \omega_i}{c}\hat{k}$$



Producing Photon Pairs

- Non-Linear Fiber Optics

No second order nonlinearity!

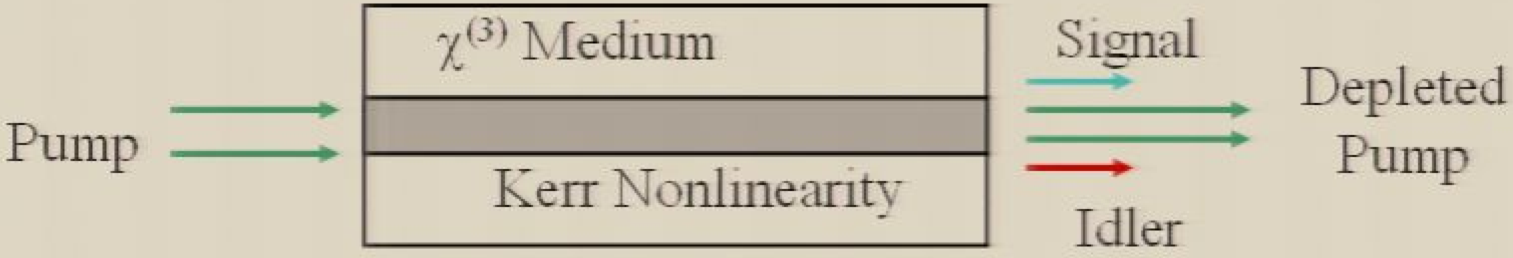
$$\mathbf{P} = \varepsilon_0(\chi^{(1)}\mathbf{E} \ + \qquad\qquad \chi^{(3)}\mathbf{EEE} \ + \ \ldots)$$

- Third order effects:
  - Self & Cross Phase Modulation

$$\mathbf{E}_1(r,t) \rightarrow \mathbf{E}(r,t)\exp\left(i\gamma(|E_1|^2 + 2|E_2|^2)z\right)$$

  - Four-Wave Mixing

$$\omega_1 + \omega_2 \rightarrow \omega_3 + \omega_4$$



$$\kappa = (k_{signal} + k_{idler} - k_{pump1} - k_{pump2}) + \gamma P_0 = 0, \quad \mathbf{k}_i = \frac{n_i\omega_i}{c}\hat{k}$$

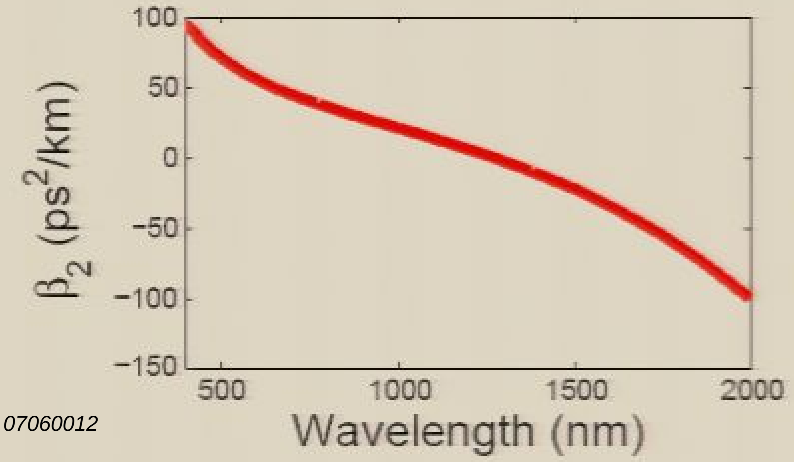
Single Pump FWM

- Wave Equation with stability analysis

$$\nabla^2 \mathbf{E} - \frac{1}{c^2}\frac{\partial^2 \mathbf{E}}{\partial t^2} = \mu_0 \frac{\partial^2 \mathbf{P}_{\mathrm{L}}}{\partial t^2} + \mu_0 \frac{\partial^2 \mathbf{P}_{\mathrm{NL}}}{\partial t^2}$$

4nd order Propagation Equation

$$i\frac{\partial A}{\partial z} = \frac{\beta_2}{2}\frac{\partial^2 A}{\partial T^2} - \frac{\beta_4}{24}\frac{\partial^4 A}{\partial T^4} - \gamma PA$$



β_2 is the chromatic dispersion of the fiber

β_4 is its second derivative

$A^2(z)$ is the pulse power

Single Pump FWM

In a linear stability analysis, an important parameter arises

$$K = \pm\sqrt{\left(\frac{\beta_2\Omega^2}{2}+\frac{\beta_4\Omega^4}{24}\right)\left(\frac{\beta_2\Omega^2}{2}+\frac{\beta_4\Omega^4}{24}+2\gamma P\right)}$$

For any gain, K must be imaginary (β_4 is small and < 0)

$\beta_2 > 0$

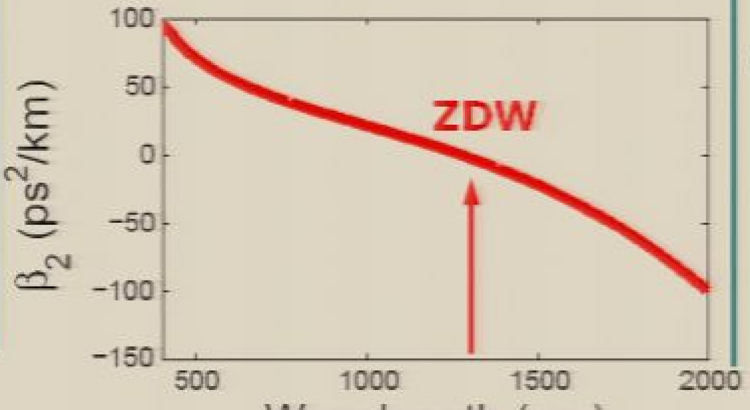
'Normal Dispersion'

(below ZDW)

$$\Rightarrow \Omega^2 < \frac{-12\beta_2}{\beta_4}$$

$\beta_2 = 0$

Zero Dispersion



$\beta_2 < 0$

'Anomolous Dispersion'

(above ZDW)

$$\Rightarrow \Omega^2 < \frac{4\gamma P}{|\beta_2|}$$

Standard SMF – Single Pump

SMF index profile

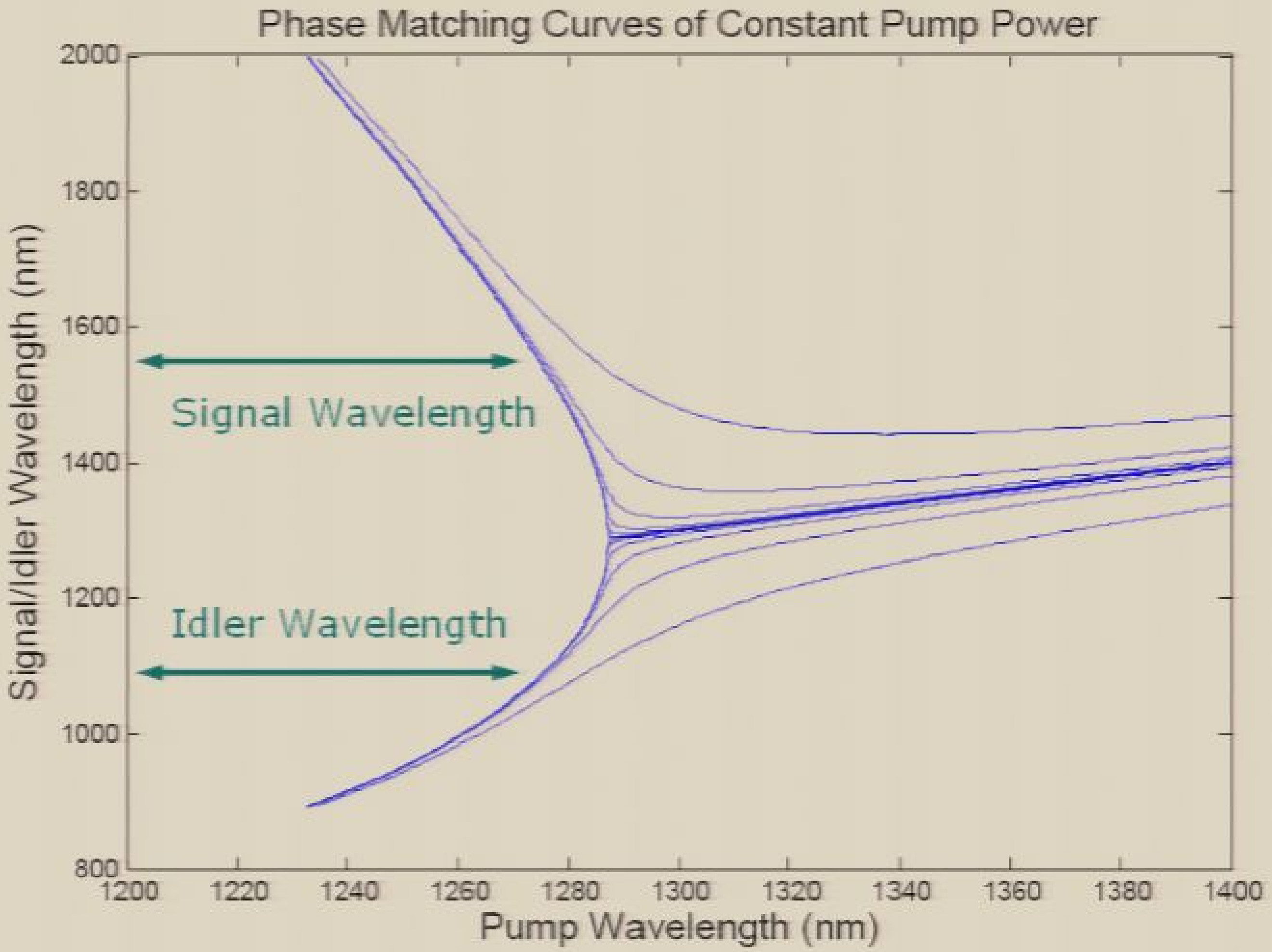
Parameters:

Pump Wavelength

Pump Power

Calculate:

Signal & Idler



$$\kappa = (k_{signal} + k_{idler} - k_{pump1} - k_{pump2}) + \gamma P_0 = 0$$

Standard SMF – Single Pump

SMF index profile

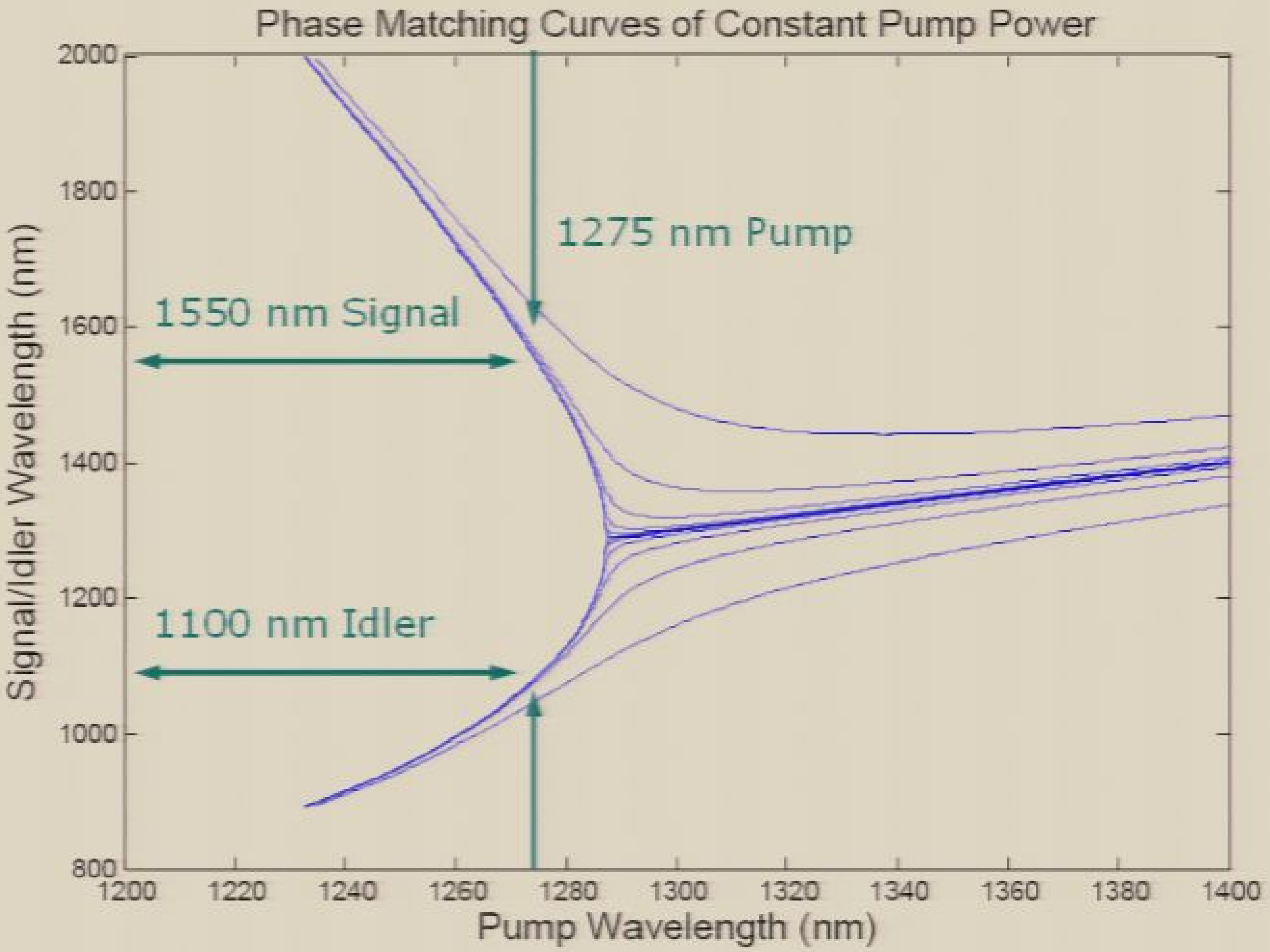
Parameters:

Pump Wavelength

Pump Power

Calculate:

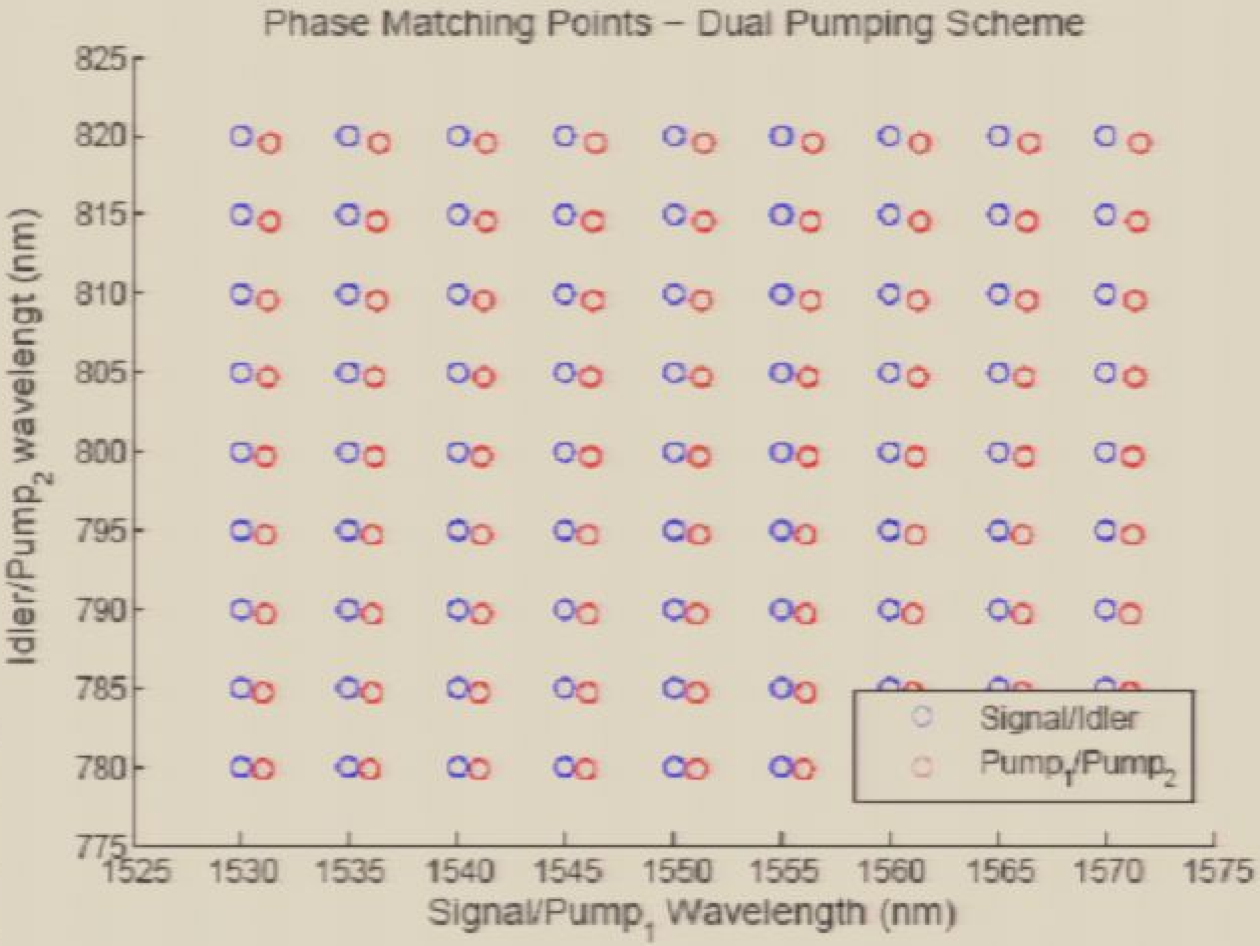
Signal & Idler

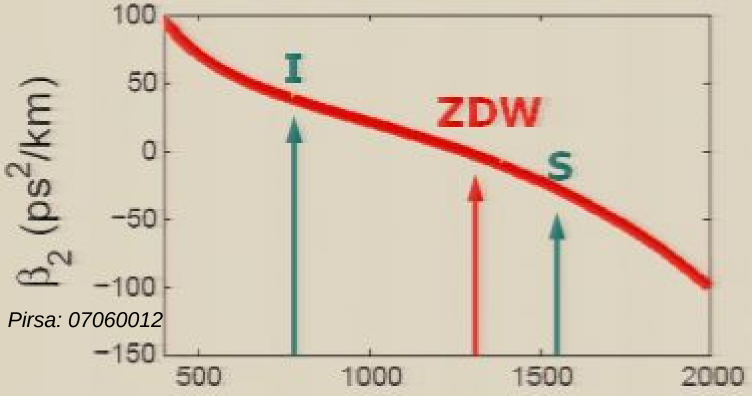


Single Pump in Standard Fiber misses the target!

Standard SMF – Dual Pump

Phase Matching Occurs when Signal/Idler are only 1 nm from pumps!

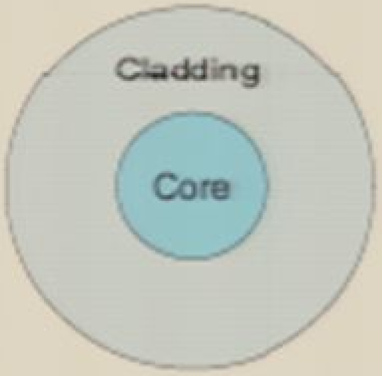




Gap decreases as wavelength asymmetry

Standard vs. Photonic Crystal Fiber

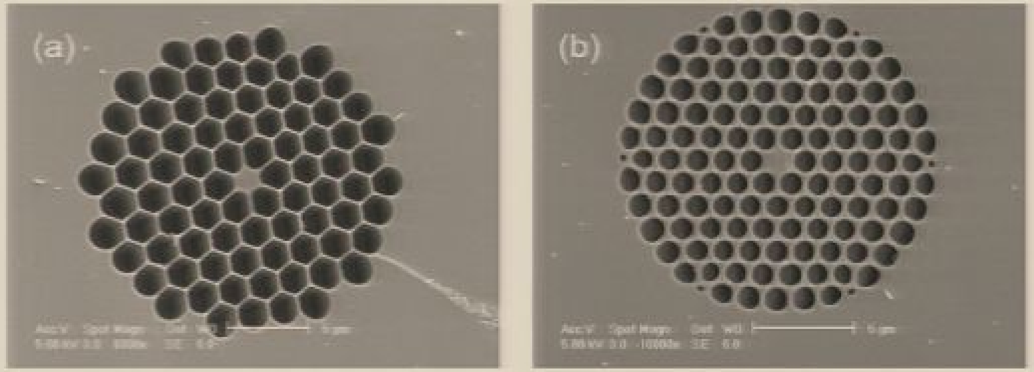
Standard Fiber



Silica structure with doped core to raise refractive index and allow for total internal reflection

Effective refractive index and ZWD shifted only slightly from material refractive index and ZWD

Photonic Crystal Fiber



Cladding a honey-comb structure of air pockets. Effective index drastically shifted from material profile

Can shift zero dispersion wavelength to much smaller wavelengths

Smaller core radius gives stronger nonlinear effects.

Photonic Crystal Fiber - Step-Index Model

- Modelling Effective Refractive Index of Photonic Crystal Fiber:
    - Model the core as pure silica
    - Model the 'cladding' as a mixture of silica and air
    - Use Step-Index fiber model

$$n(r)=\begin{cases}= n_{silica}, & 0<r<a \\ =(AirFraction)n_{air}+(1-AirFraction)n_{silica}, & a<r<\infty\end{cases}$$

- Calculating effective index in a step-index fiber
    - Solves wave equation with tangential E, H continuity

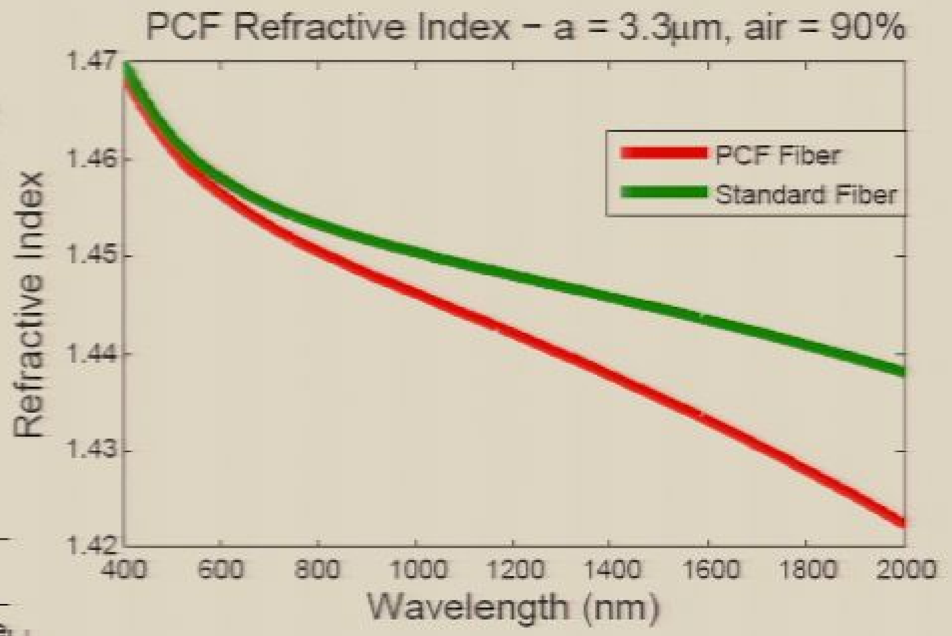
$$h=a\sqrt{n_1^{\;2}-n_{eff}^{\;2}},\quad q=a\sqrt{n_{eff}^{\;2}-n_2^{\;2}},\quad V=a\sqrt{n_1^{\;2}-n_2^{\;2}}=\sqrt{h^2+q^2}$$

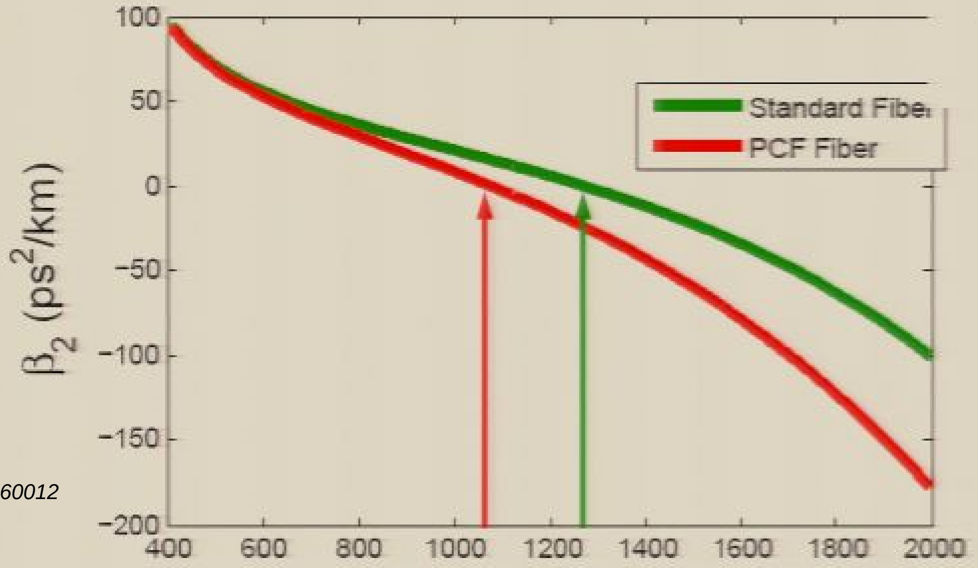
$$h\frac{J_1(h)}{J_0(h)}=q\frac{K_1(q)}{K_0(q)}$$

Same equation for all step index fibers!

Photonic Crystal Fiber

- Can easily calculate effective index for a range of PCFs (given core radius and air fraction)





- Can create a dispersion with the ZDW we want by adjusting parameters

Photonic Crystal Fiber

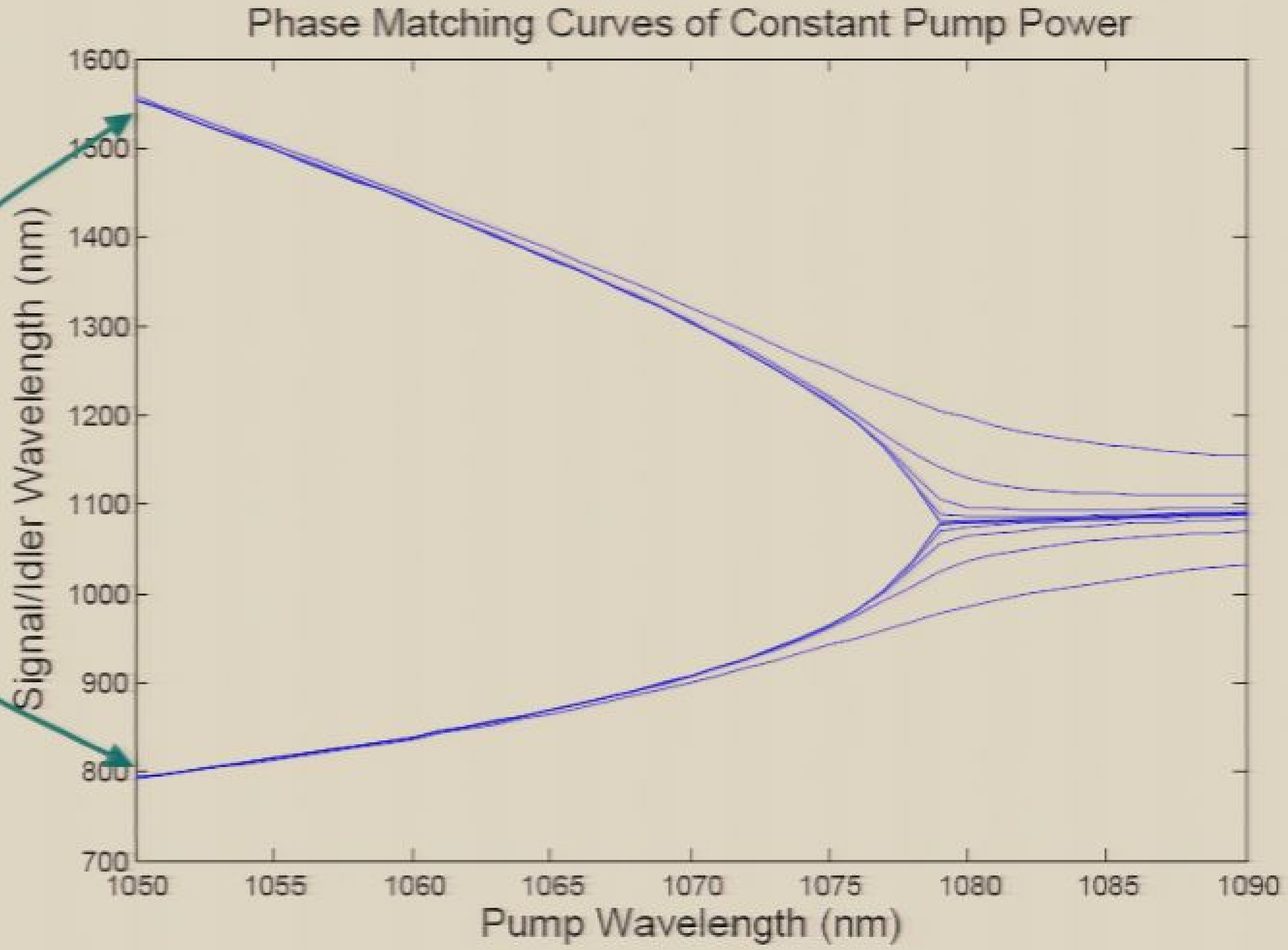
PCF index profile

a = 3.3 μm

Air = 90%

1550 nm Signal

800 nm Idler



PCF demonstrates Potential to produce widely separated photon pairs

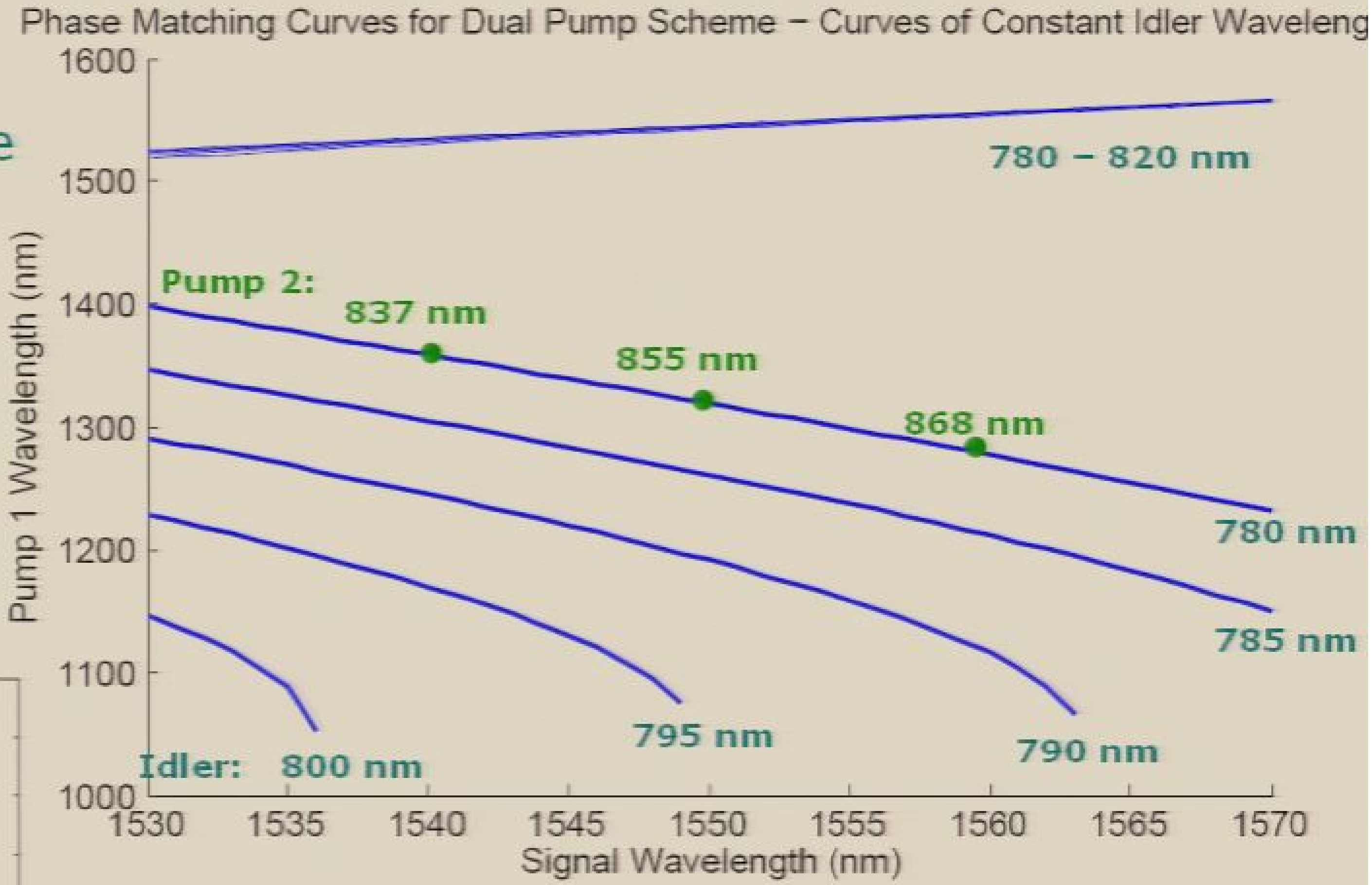
Photonic Crystal Fiber

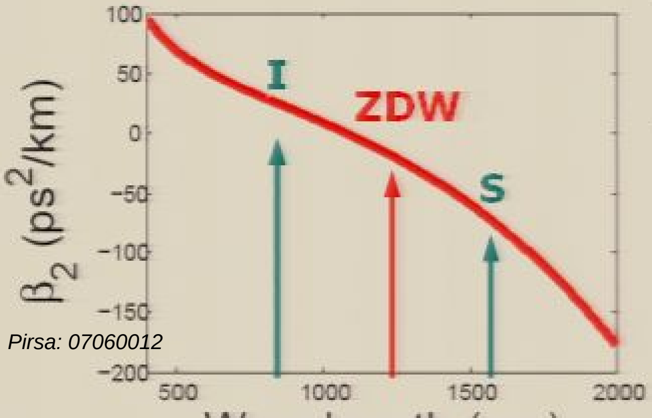
Dual Pump

PCF index profile

a = 3.3 µm

Air = 90%





PCF with a dual pumping scheme shows promise as a source of entangled Photon Pairs

Conclusions

- To produce entangled photon pairs at widely separated wavelengths:
  - Standard Optical Fiber does not have the right properties
  - Photonic Crystal Fiber with single or dual pumps shows great promise

  - There are Other Schemes (polarization, multimodes, complex dispersion profiles) with potential that need to be examined
  - Availability of photonic crystal fibers and high power lasers that meet phase matching conditions

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