# Degenerate Four-Wave Mixing in Fiber Squeeze Light: Generation and Characterization

Cassidy Bliss

# Introduction to Squeeze light

- Squeezed States of light have noise below the standard quantum limit in one quadrature component
- One property of uncertainty is lowered and consequently the others are increased as per Schrodinger's Uncertainty Principle
- In our case, we generate two-mode squeezed vacuum or twin-beam state (TWB), which means that the intensities of the light beams are correlated with each other at the quantum level.

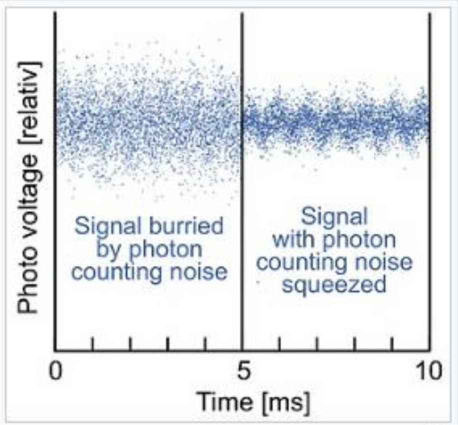
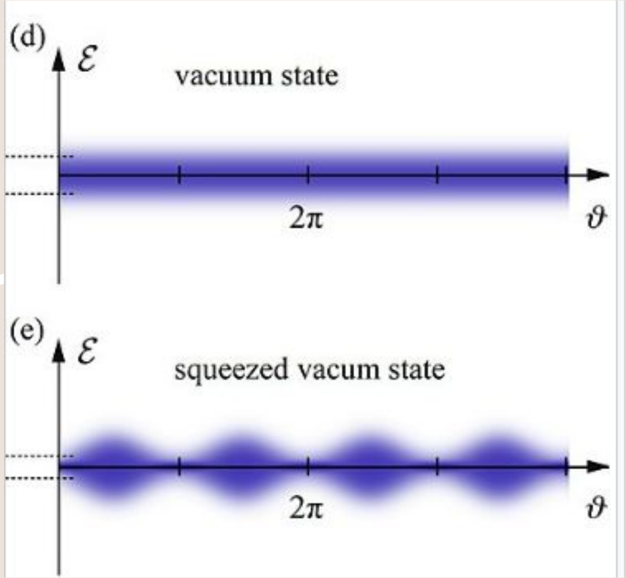
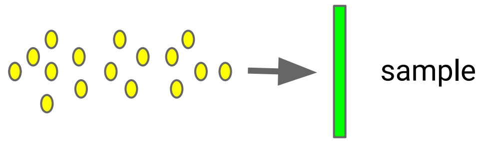



Fig. 4: Photo voltages of a photo diode detecting light.

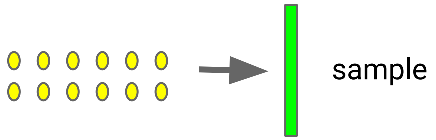


# Why are We Using Squeeze light over Classical Source?

- In our UCNP fluorescent microscope, our system is designed around a two-photon upconversion process within the nanoparticles with a 1550 nm light source.
- For biological applications, our concept relies on two photons arriving at the sample at the same time to avoid cellular damage
- We hope to see an enhancement of this upconversion process by using a squeeze light source, increasing our signal to noise ratio, and allowing lower input power with comparable results for imaging purposes without risk of cellular damage.



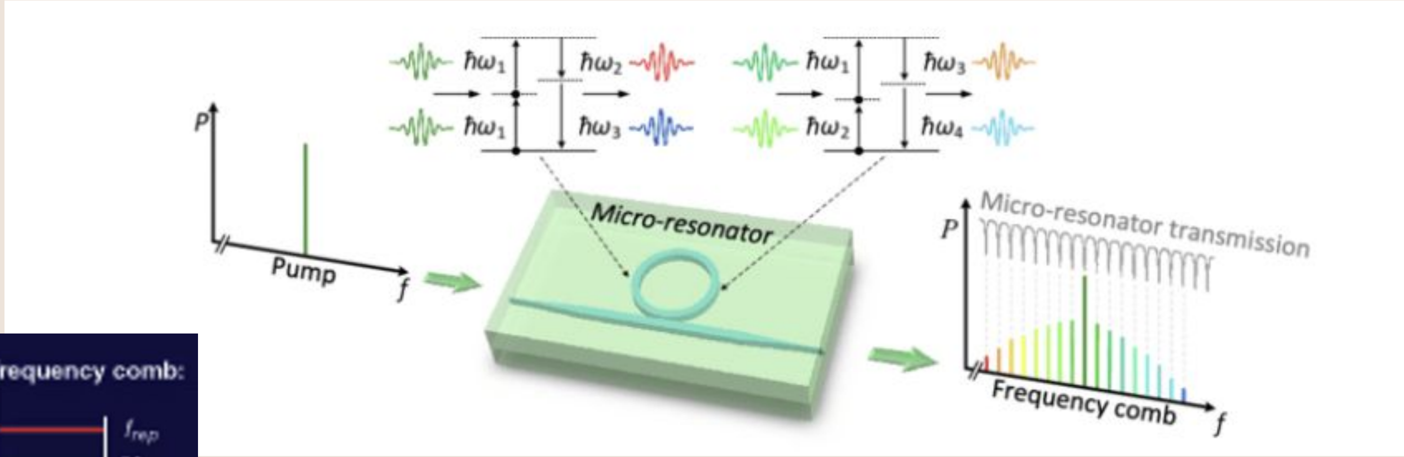

Photons from classical source



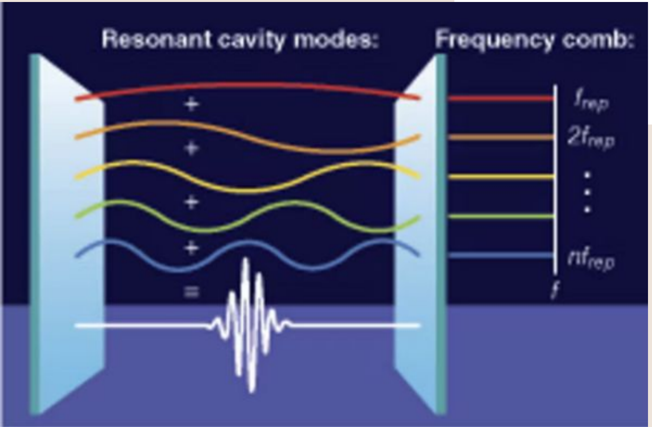

Photons from squeezed light source

# Kerr Optical Frequency combs

Kerr optical frequency combs are sets of equidistant spectral lines generated within a resonator cavity pumped by a CW laser. The dependence of refractive index on the intensity of the optical power resulting from the Kerr effect causes a third-order nonlinear process known as degenerate four wave mixing (FWM).



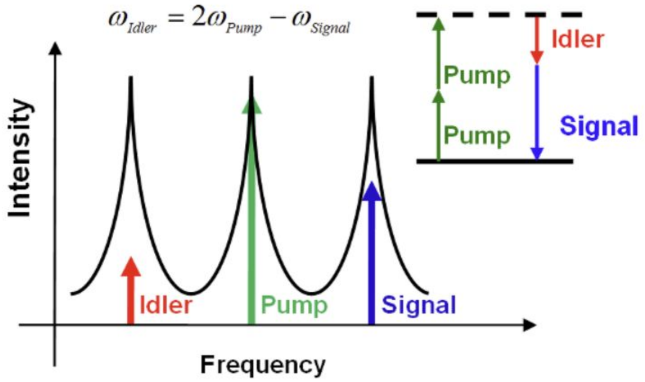

- Generally a resonator needs both an ultrahigh quality factor and a Kerr nonlinearity



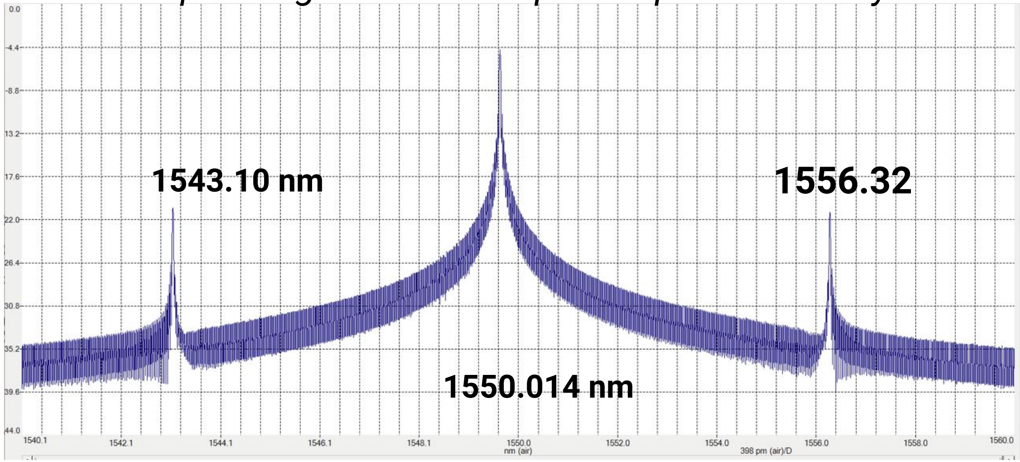

- This traps the pump photons long enough in the toruslike eigenmodes to host this nonlinear interaction

# Degenerate Four-Wave Mixing in Optical Fiber Method for Generating Squeeze Light

- Below a certain threshold of pump power, the intracavity photons remain in a single cavity mode and their frequency remains mostly the same as the pump laser
- Above a this threshold, photons are steadily transferred through FWM to neighboring cavity modes under the right conditions
- While this process can be cascaded to hundreds of modes (kerr combs) we focus on a small pump power range that allows for only 3 modes to exist within the cavity, resulting in 2-mode squeeze light (3 Kerr Combs)




*Our Squeezing as seen on Optical Spectrum Analyzer*



# Behavior Above and Below Threshold Pump Power

<u>Below Threshold:</u>

- From a quantum perspective, the pump field is actually at the origin of spontaneous four-wave mixing where two pump photons are symmetrically up- and down-converted in the Fourier domain, leading to simultaneous and spontaneous generation of *signal* and *idler* photons (sometimes called parametric fluorescence), following the photonic interaction:

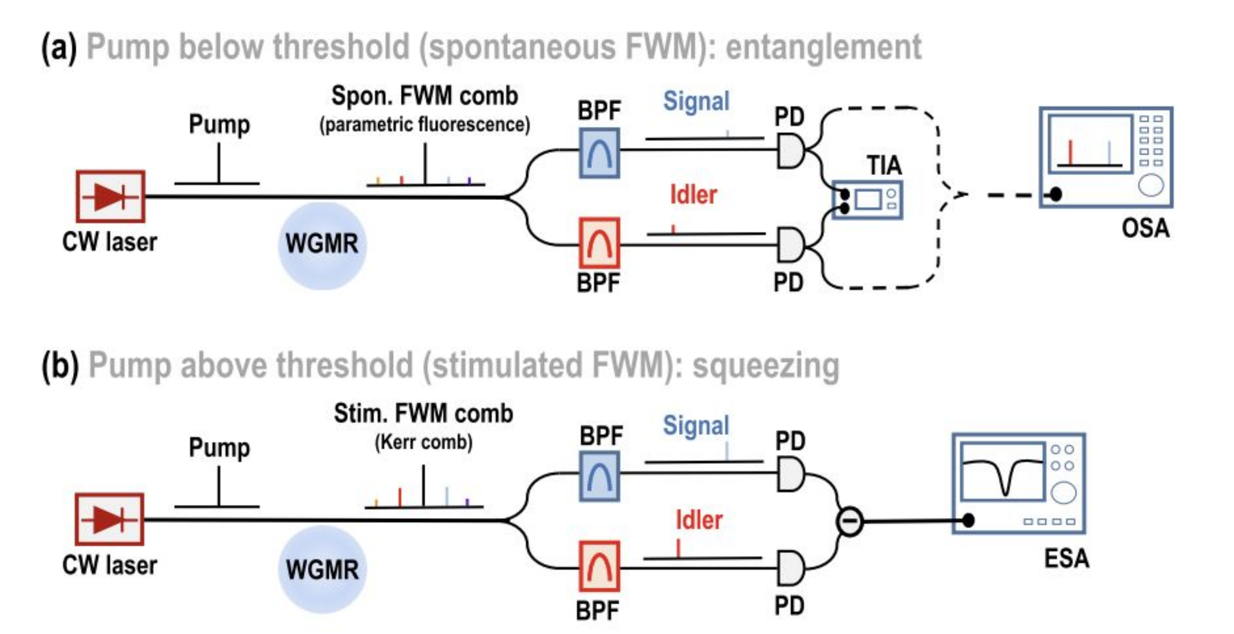
$$2h_{bar}\omega_p \rightarrow h_{bar}\omega_i + h_{bar}\omega_s$$

- Spontaneous four-wave-mixing can only be understood and analyzed from a fully quantum perspective, because it results from the coupling between the intracacity pump photons and the vacuum fluctuations of the various side modes.
- Below threshold, signal and idler are entangled photon pairs, correlated to one another at the quantum level

# Behavior Above and Below Threshold Pump Power

<u>Above Threshold:</u>

- Above threshold, the photonic interaction previously shown becomes steadily sustained (stimulated FWM)
- From a classical perspective, the signal and idler modes are correlated twin beams in the frequency domain, yielding a roll pattern in the spatial domain
- It has been demonstrated that the intensity difference between the signal and idler exhibits fluctuations below the standard quantum-noise limit
- By analogy to laser theory, it is considered that this phenomenon corresponds to stimulated four-wave-mixing



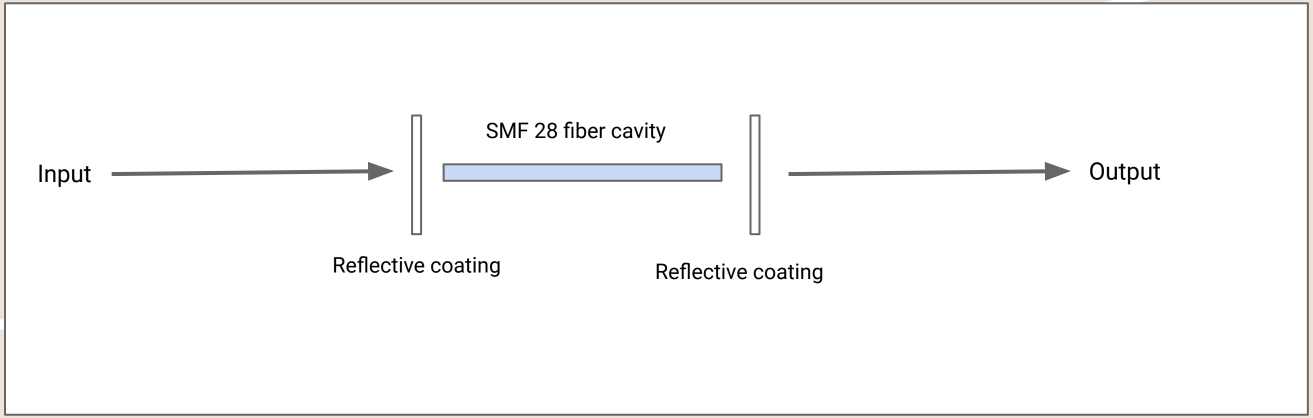
# Our Squeeze Light Source

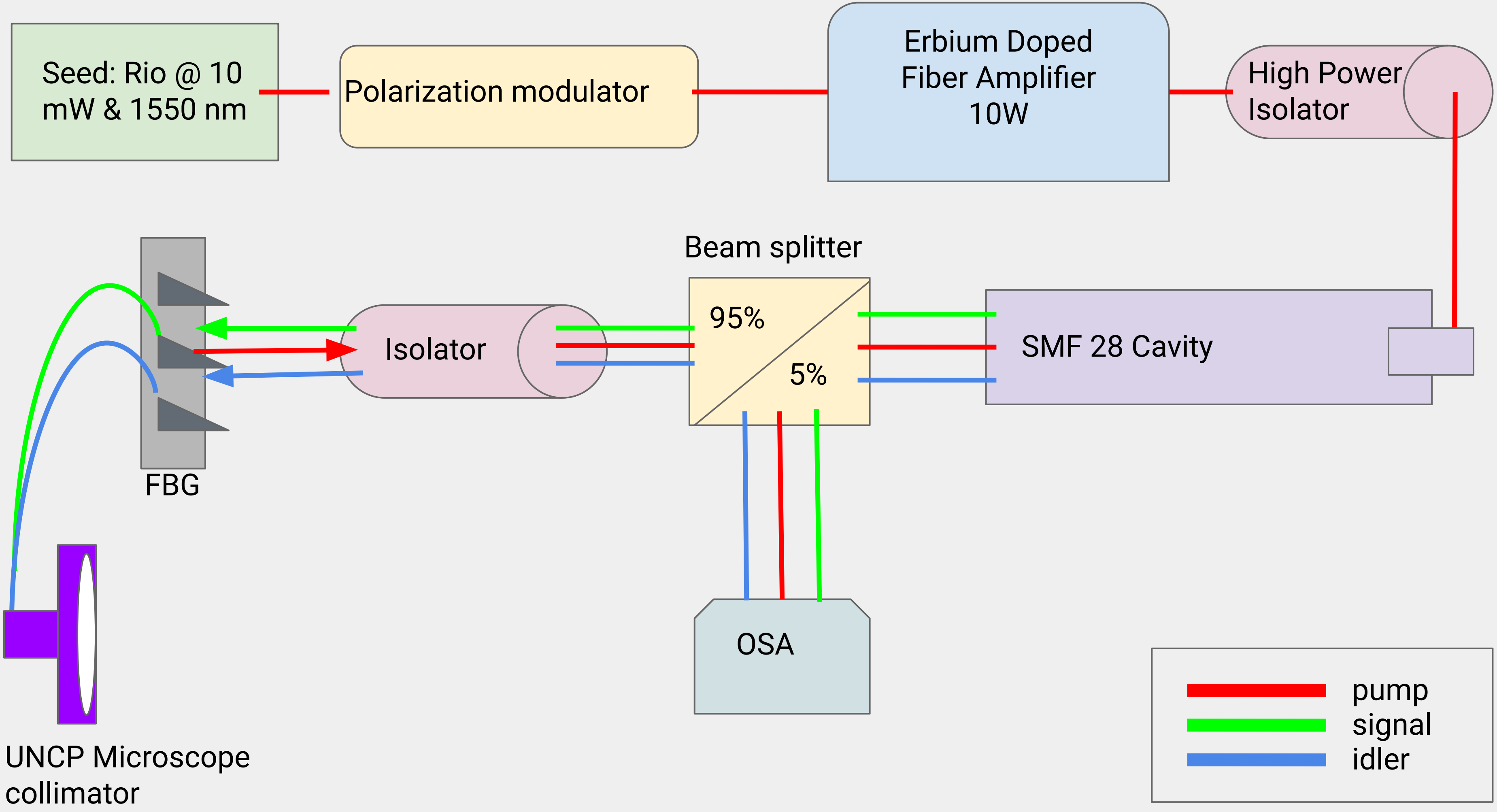
General Specs:

- Seed from Rio tunable laser pump at 10 mW
- Using fiber as resonance cavity: SMF 28: 1 cm in length
- Thermal control tuning to bring pur system up to resonance
- Output signal and idler of equal polarizations initially also mixed with pump signal until filtered out
- Signal and idler have different frequencies

# Add Through Coupling

- The configuration in our squeeze light system is considered add-through coupling
- This architecture involves a single coupler that is used to pump the cavity and retrieve the comb signal, detected at the through port
- Add-through coupling allows for limited coupling losses and therefore low threshold power for Kerr comb generation
- The disadvantage of this coupling is that the output signal is a superposition of the intracavity and a portion of the pump which is directly passing through the coupling waveguide




Seed: Rio @ 10 mW & 1550 nm
Polarization modulator
Erbium Doped Fiber Amplifier 10W
High Power Isolator
Beam splitter
95%
5%
SMF 28 Cavity
Isolator
FBG
OSA
UNCP Microscope collimator
pump
signal
idler

# Characterizing Squeeze Light

1

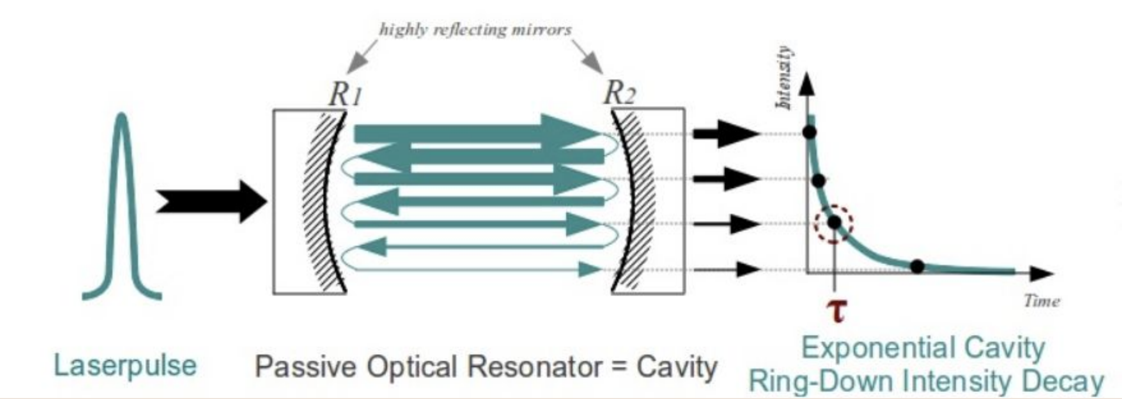
**Quality Factors**

- Quality factors are used to describe the efficiency of a resonance cavity
- Cavities have both an an intrinsic and loaded quality factor
- The various linewidths of resulting frequencies are related to their corresponding quality factors by:

$$\Delta\omega_{int,ext,tot} = \frac{\omega_L}{Q_{int,ext,tot}}$$

- Quality factors can be experimentally determined using the cavity-ring down method:

$$Q = \omega_0 \tau_p$$



# Characterizing Squeeze Light

1 **Quality Factors**

$$\rho = \frac{Q_{ext}}{Q_{tot}}$$

- The ratio between out-coupling and total losses can be interpreted as the ratio between the number of detected photons versus the total number of annihilated photons.
- This parameter, p, represents a direct indicator of the squeezing efficiency
- As p→ 1 : quasiperfect squeezing at zero frequency
- As p→ 0 : leads to no squeezing at all frequencies

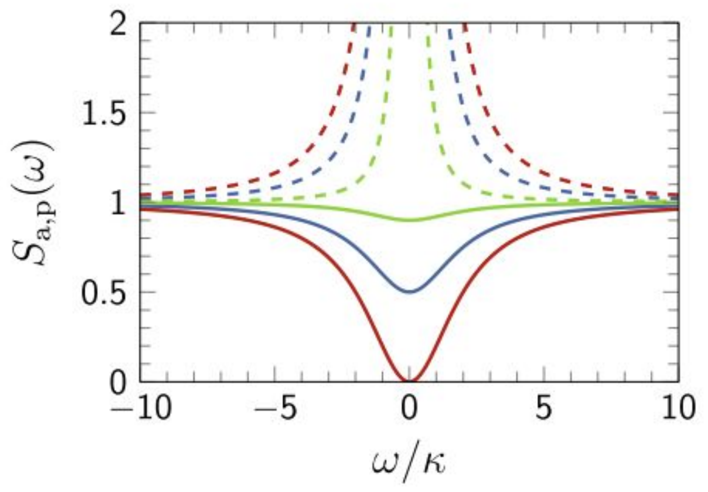



FIG. 6. Power spectra of pure amplitude and phase quadratures for different values of the squeezing parameter $\rho$. The solid lines correspond at the same time to the photon number difference spectrum of Eq. (105) and to the pure amplitude quadrature spectrum of Eq. (137), since both are identical. The dashed lines correspond to the phase quadrature spectrum of Eq. (138). Green lines, $\rho = 0.1$; blue lines, $\rho = 0.5$; red lines, $\rho = 1$. We have arbitrarily set $\kappa_p \equiv \frac{1}{3}\kappa$.

# Characterizing Squeeze Light

2 **Theoretical Squeezing Factor (relative to shot noise)**

The Squeezing factor gives us the difference between SNL and squeeze light noise (in dBm)

$$S(\Omega) = 1 - \frac{n_c n_d}{1 + \Omega^2 \tau_c^2}$$

$\Omega =$ *sideband frequency,*

$n_c = 1 - \frac{Q_L}{Q_i}$ = ratio of coupling losses to total losses

$\tau_c =$ cavity photon lifetime

$n_d$ = the detection efficiency

In essence, the squeezing factor will tell us the expected noise loss of the given system, which will tell us how 'well' the squeeze light is being generated as it relates to pairs of entangled photons at the source.

The quality of squeezing quantitatively depends on the ratio between the losses given by the intrinsic quality factor Qi and coupling coefficient determined by the loaded quality factor QL

Experimentally, we can measure the squeezing factor by finding the shot noise level of our system with a classical laser source and then measuring the noise of our squeeze light system

# Preliminary Theoretical Results: Squeeze Factor

```
%key values
lambda_seed = 1550.014;
lambda_sig = 1543.10;
W0=2*pi*3*10^8/lambda_seed;
W_offset = 2*pi*3*10^8/lambda_sig;
Qi = 50000000;
Ql = 20000000;
Tc = Ql/W0;
sbf = (W0-W_offset)*(1/6.28);
Qd = 0.85;

%Key value description:
%Qi = intrinsic quality factor (dimensionless)
%Ql = loaded quality factor (dimensionless)
%Tc = cavity photon lifetime (s)
%sbf = side band frequency (Hz)
%Qd = quantum efficiency of detector (dimensionless)

%test function/calculate SF:
x = squeezeCalc(Qi,Ql,Tc,sbf,Qd);
disp('Theoretical Squeeze Factor:')
disp(x)
disp('dBm')


%Squeeze factor function
function squeezeFactor = squeezeCalc(Qi,Ql,Tc,Qd,sbf)
    Nc = 1-(Ql/Qi);
    squeezeFactor= 1-((Nc*Qd)/(1+(sbf^2*Tc^2)));
end
```

```
Theoretical Squeeze Factor:
    3.6504

dBm
```

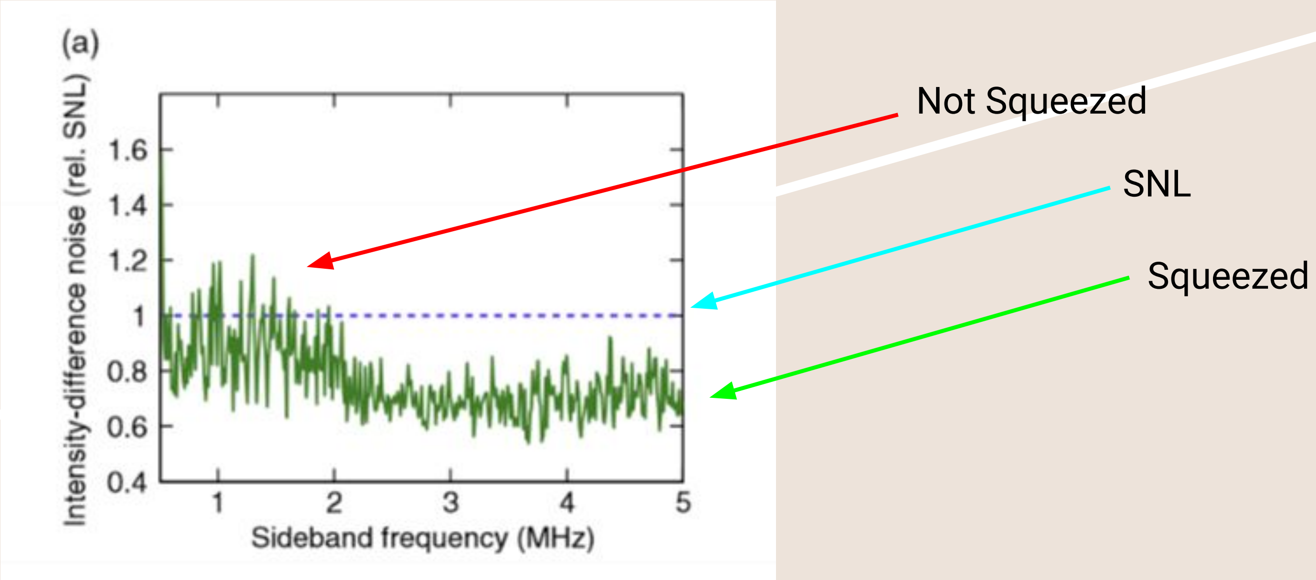
*Published with MATLAB® R2021b*

- Uncertainty in this calculation
- Not 100% sure that all parameters are correct/in correct units

# Characterizing Squeeze Light

3 **Intensity Difference Noise Between Twin Beams**

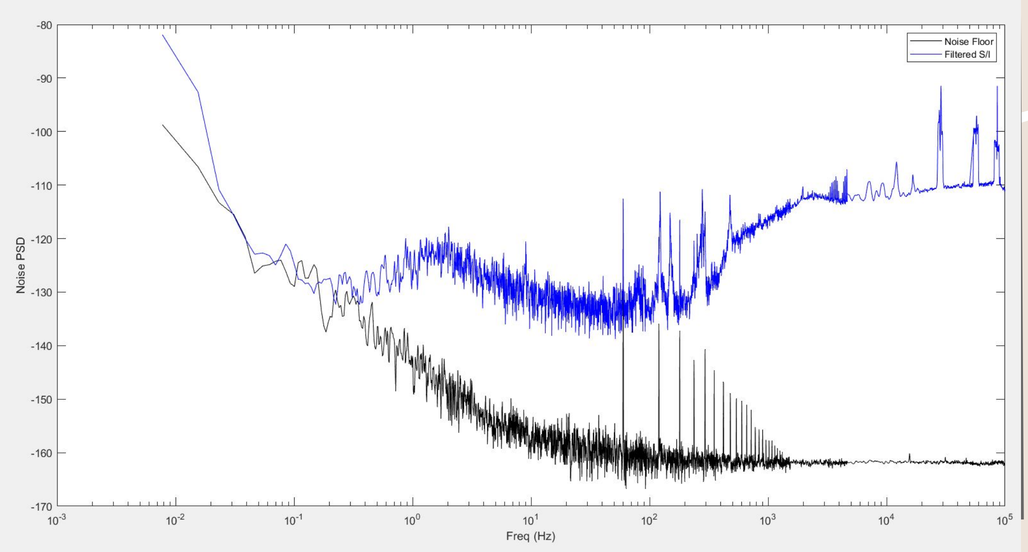
- The noise measurement between the signal and idler output beams using a balanced detector can give a quantitative representation of how efficiently the squeeze light is being generated
- Squeezing occurs when this noise is reduced below the standard quantum-noise limit
- A comparison of the two also requires measurement of the shot noise level (SNL)



# Characterizing Squeeze Light

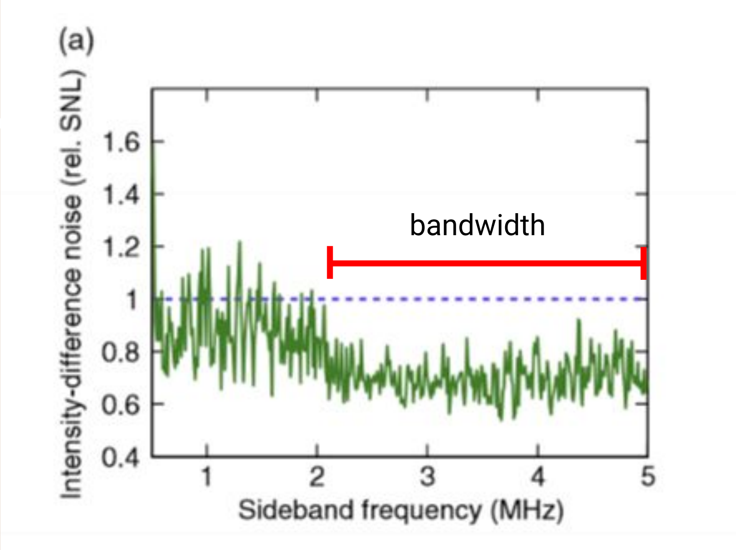
4 **Stability of Squeeze Light**

- The more stable the squeezed light, the more correlated the output beams will be and efficiency increases
- A measurement of how much the squeeze light fluctuates in power over a bandwidth
- Linewidth (FWHM) of output frequency signal can indicate stability

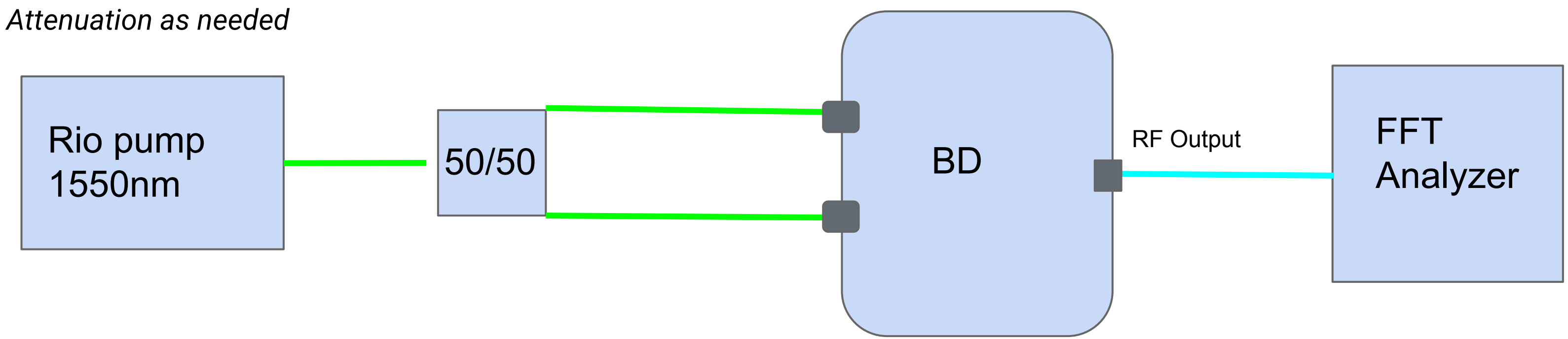



5 **Squeezing Bandwidth**

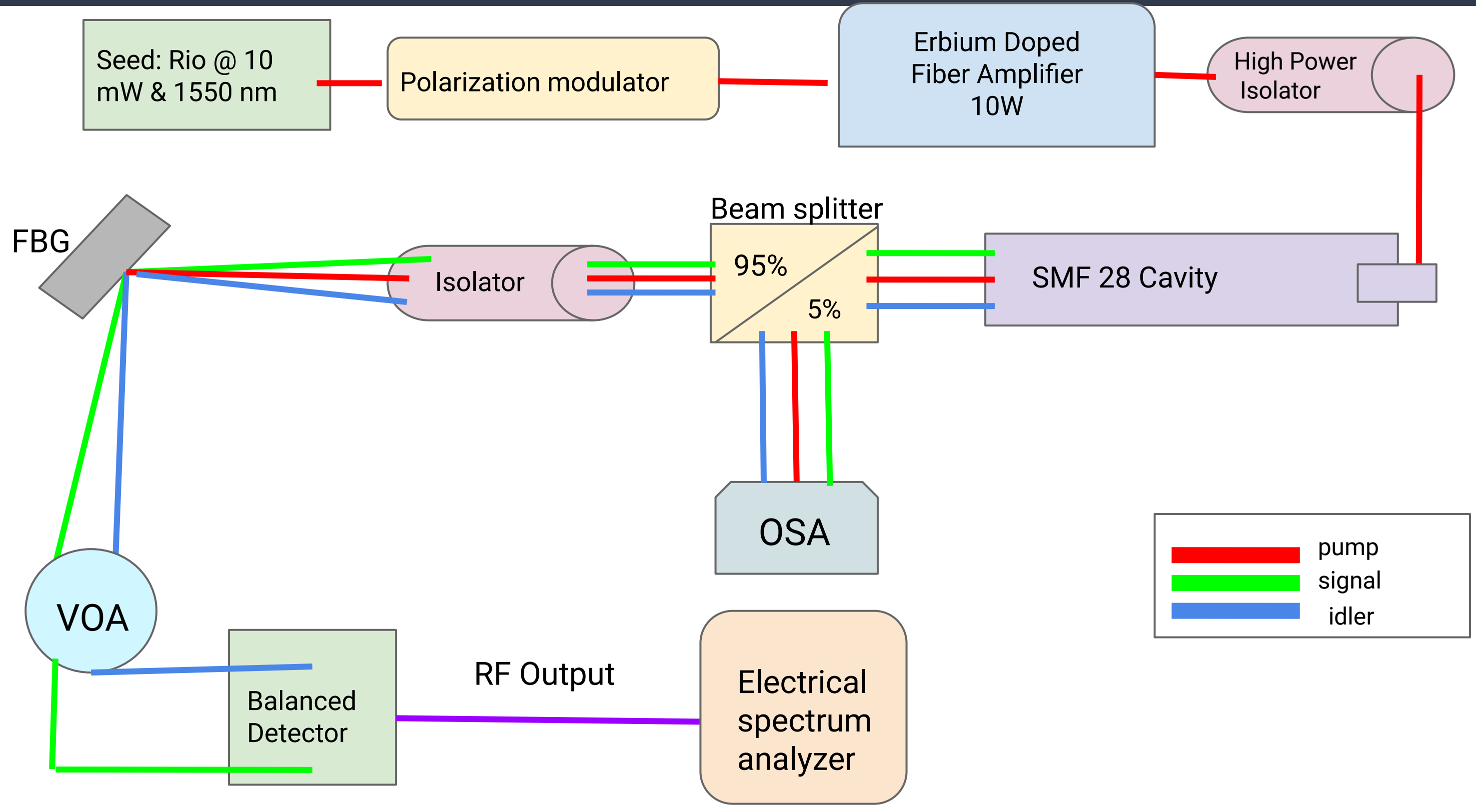
- A measurement of the bandwidth of the squeeze noise that is below the SNL



# Experimental Setup for Shot Noise Calibration



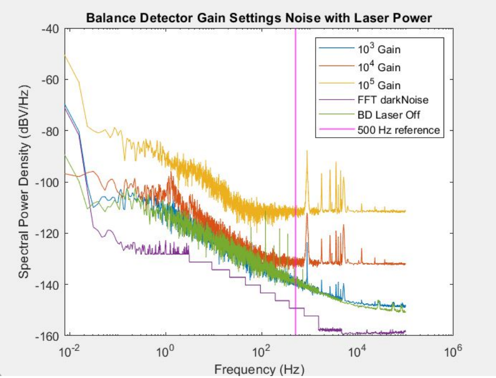
# Experimental Setup for Squeeze Noise Measurement



# Experimental Goals & Procedures

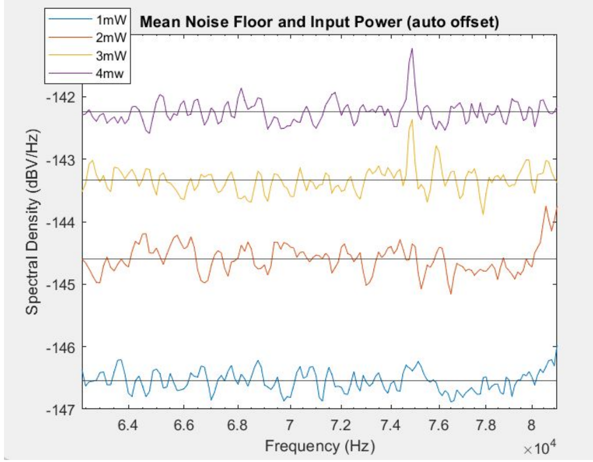
**Account for Noise Sources and Optimization**

- Laser Noise
- FFT Analyzer Noise
- BD Noise
- Optimize and quantify stability of source




**Measure SNL**

- Measure the noise floor of the squeeze light system using RIO laser source




**Measure Squeeze Light Noise**

- Filter out the pump and separate the signal and idler with Fiber Bragg Grating
- Mix with Local oscillator at higher frequency reference signal
- Input signal and idler separately into Balanced detector
- Tap into the RF output ESA for noise measurement