Polarization extinction ratio and polarization dependent intensity noise in long-pulse supercontinuum generation

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Motivation

1. Polarisation sensitive applications
2. Low-noise polarisation sensitive (PS)-OCT using supercontinuum (SC)

What we discovered?

1. Polarisation varies across the SC spectrum
2. Polarisation Extinction Ratio (PER) $>10$ dB
3. Relative Intensity Noise (RIN) differs on long wavelength edge of supercontinuum
Polarisation intensity noise in supercontinuum

Experiments

1. Spectrum characterisation
2. Noise measurements in two linear polarisation states
3. Statistical analysis

System setup

SuperK -> Lens -> Polarizer -> Filter -> Removable mirror -> Integrating sphere -> OSA

GHz oscilloscope

Narrow band pass filter (10 / 12 nm)

High speed photo detector
Polarisation extinction ratio in supercontinuum

Supercontinuum source
- SuperK Extreme (NKT Photonics)
- Pulse repetition frequency **80 MHz**
- Pulse duration **5 ps**

Transmission spectrum

PER

Power spectral density (dB/nm)

PER (dB)

Wavelength (nm)

Min at 100%
Max at 100%
Min at 67%
Max at 67%
Min at 33%
Max at 33%
Polarisation intensity noise in supercontinuum

Supercontinuum noise statistics

1. Gaussian near pump
2. Rogue wave (long tailed) statistics near edges
3. Higher power decreases noise at fixed wavelength
4. Measured: RIN and skewness

Optical Rogue Waves
[Solli, Ropers, Koonath & Jalali, Nature 2007]

Polarization dependence of noise

1. Pulse-to-pulse polarization state fluctuates due to modulation instability and Raman;
2. Nonlinear processes => Spectral profile of polarization will change with power

GV matching known since work of [Beaud et al., JQE 1987]
[Stone, Knight, Opt Exp 2008]
Polarisation intensity noise in supercontinuum

Measurement protocol:
(A) Select direction of max power at pump wavelength
(B) Record RIN along 2-orthogonal directions (min & max)

System set-up

SuperK → Lens → Polarizer → Filter → Mirror → Narrow band pass filter (10 / 12 nm) → High speed photo detector → GHz oscilloscope
Polarisation intensity noise in supercontinuum

1. Find peak in each pulse of total 1000 pulses train

We define a collection of pulses as $P_k = P_1, P_2, P_3, \ldots, P_n$

where

$$
\begin{align*}
P_1 &= P_{1,max} - P_{1,min} \\
P_2 &= P_{2,max} - P_{2,min} \\
P_3 &= P_{3,max} - P_{3,min} \\
& \vdots \\
P_n &= P_{n,max} - P_{n,min}
\end{align*}
$$

$P_{n,min}$ is the base line, zero level

$P_{n,max}$ is the maximum peak value for each pulse,

2. Calculate noise statistics

For skewness refer to [Dudley, Coen, Opt Lett 2002]

$$
RIN = \frac{\text{var}(p)}{\langle \bar{p} \rangle}
$$

sample average, $\text{mean}(p)$ as

$$
\bar{p} = \frac{1}{n} \sum_{k=1}^{n} P_k
$$

Sample variance, $\text{var}(p)$ as

$$
\text{var}(p) = \frac{1}{n-1} \sum_{k=1}^{n} (P_k - \bar{p})^2
$$
Polarisation intensity noise in supercontinuum

- P=100%
- P=67%
- P=33%

Power spectral density (dB/nm) vs. Wavelength (nm)

Max polarisation vs. Min polarisation

RIN (×10)% vs. Wavelength (nm)
Polarisation intensity noise in supercontinuum

- **P=100%**
- **P=67%**
- **P=33%**

- **550 nm at 100% pump**
- **1000 nm at 100% pump**
- **1650 nm at 100% pump**
Conclusions

1. Noticeable power difference of polarisation modes (PER) at long wavelengths
   • Preliminary numerical simulations confirm this for close to 50/50 pumping

2. Same type of noise observed in both polarisations
   • RIN is pump power dependent
   • RIN increase towards spectral edges
   • Lowest RIN at pump wavelength

3. PER but no difference in noise (at red edge)

4. RIN at OCT wavelengths are low (700-950 nm) – good for ultra broadband & high-resolution OCT applications

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2nd Canterbury Conference on OCT (emphasis on broadband optical sources)

Save the date!
Sept 6th – 8th, 2017

http://2ccoct.aogkent.uk

Home

Date: 6th – 8th of September 2017
Venue: University of Kent, Canterbury (United Kingdom)

Chairs:
Adrian Podoleanu, University of Kent, Canterbury, United Kingdom
Ole Bang, Technical University of Denmark, Copenhagen, Denmark
Polarisation intensity noise in supercontinuum

Supercontinuum noise statistics

1. Rogue wave (long tailed) statistics, spectral PER
2. Pulse-to-pulse polarisation fluctuation
3. Two parameters are measured: RIN and skewness

(A) Relative intensity noise at 2 orthogonal polarisations:

$$RIN = \frac{\sigma^2}{\langle x \rangle}$$

$$\frac{1}{n} \sum_{i=1}^{n} (x_i - \bar{x})^3$$

(B) Skewness:

$$m_3 = \frac{1}{n-1} \sum_{i=1}^{n} (x_i - \bar{x})^3 / \left( \frac{1}{n-1} \sum_{i=1}^{n} (x_i - \bar{x})^2 \right)^{3/2}$$