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Experimental Verification of Polarization Multiplexing for Suppressing FWM

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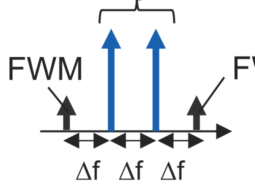
Background: Four Wave Mixing (FWM)

- Four Wave Mixing (FWM) is a kind of 3rd-order fiber non-linear effect, in which new light waves (FWMs) are generated at the sum and difference of existing 2 or 3 wavelength optical signals
- If this new light signal overlaps with another optical signal channel, the transmission quality is degraded

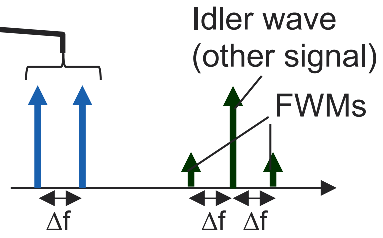
(1) Partially-degenerate case (two waves)



Two pump waves (signals)
- with the frequency spacing Δf
- with the same polarization

Two FWM products (FWMs) are generated on both sides of two pumps with frequency separation Δf.
- FWMs are the same polarization as the pumps.

(2) Non-degenerate case (three waves)



Two FWM products (FWMs) are generated on both sides of the idler wave with the frequency separation Δf.
- Polarization of the Idler wave is arbitrary.
- FWMs are the same polarization as the idler wave.

Any signals can act as two pumps and idler, therefore, total six FWMs can be generated from three signals.

Four-wave mixing (partially-degenerate)

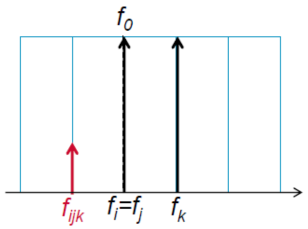
FWM frequency:
$f_{ijk} = f_i + f_j - f_k$

FWM power:
$P_{ijk} = \left(\frac{D_{ijk}}{3}\gamma L\right)^2 P_i P_j P_k e^{-\alpha L}\eta$, where $\gamma = \frac{2\pi n_2}{\lambda A_e}$

FWM efficiency:
$$\eta = \frac{\alpha^2}{\alpha^2 + \Delta\beta^2}\left(1 + \frac{4e^{-\alpha L}\sin^2(\Delta\beta L/2)}{(1 - e^{-\alpha L})^2}\right)$$

Phase matching condition:
$\Delta\beta = \beta_i + \beta_j - \beta_k - \beta_{ijk}$

$$\Delta\beta \approx \frac{2\pi\lambda^2}{c}(f_i - f_k)(f_j - f_k)\left[D(\lambda) - \frac{\lambda^2}{c}\left(\frac{f_i + f_j}{2} - f_{ijk}\right)\frac{dD}{d\lambda}\right]$$



Co-polarization is assumed.

FWM conversion efficiency is maximum for phase-matched condition, $\Delta\beta = 0$.

This occurs when the zero dispersion frequency, $f_0 = f_i$ or f_k.

$D_{ijk} = 3$ for partially-degenerate mixing (2 distinct inputs)

Four-wave mixing (non-degenerate)

FWM frequency:
$f_{ijk} = f_i + f_j - f_k$

FWM power:
$P_{ijk} = \left(\frac{D_{ijk}}{3}\gamma L\right)^2 P_i P_j P_k e^{-\alpha L}\eta$, where $\gamma = \frac{2\pi n_2}{\lambda A_e}$

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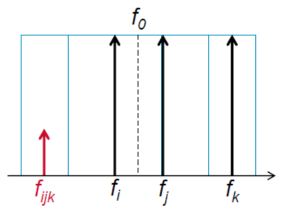


Co-polarization is assumed.

FWM conversion efficiency is maximum for phase-matched condition, $\Delta\beta = 0$.

This occurs when the zero dispersion frequency, f_0, is centered between two of the input frequencies.

$D_{ijk} = 6$ for non-degenerate mixing (3 distinct inputs)

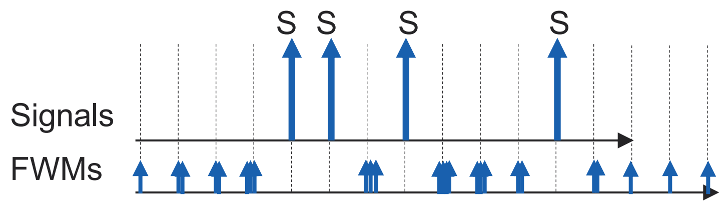
See johnson_3ca_1_0716.pdf

How to Mitigate FWM: Conventional Method

1. Unequal spacing
   – Avoid overlapping of FWMs on signals by signal frequency allocation

   <Pros>
   - Completely suppress FWM degradation

   <Cons>
   - Need wider wavelength band, may be max 4 channel (twice bandwidth for 4 waves, five times wider in 8 wave case)
   - Wider bandwidth also leads to higher chromatic dispersion, and significantly degrades signal reach
   - Wavelength accuracy should be improved to avoid the overlapping of FWMs, which increases power consumption

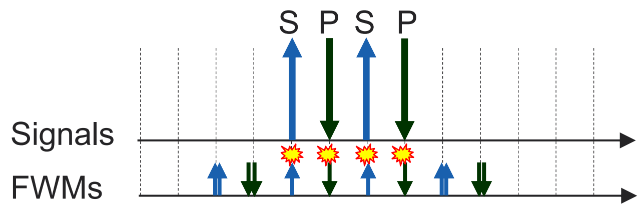


Unequal spacing

2. Polarization Interleaving
   – Reduce FWM efficiency

   <Pros>
   - Reduce number of FWM products significantly
   - Reduce FWM efficiency by doubling channel spacing

   <Cons>
   - FWM degradation cannot be completely suppressed
   - Some FWMs overlap on the signals with same polarization



Polarization Interleaving (SPSP)

*Tolerance to FWMs
- Same polarization with the signal: ~ -30 dB (inband interference)
- Orthogonal polarization with the signal: ~ -15 dB (outband interference)

If overlapping FWM has polarization orthogonal to signal, its effect can be significantly mitigated

Background: FWM and Polarization

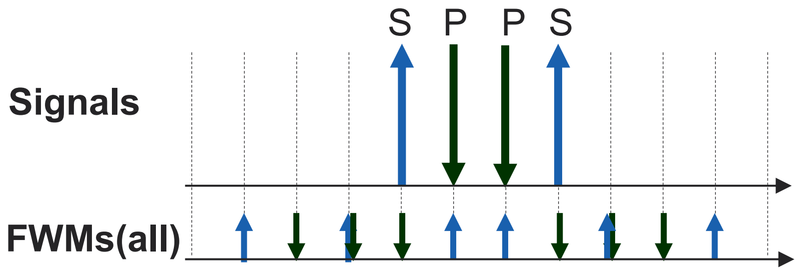
- In arbitrary polarization case,
  - Same polarization component of the two pumps generate frequency beating Δf in optical fiber
  - The idler wave is phase modulated by the beating at Δf, which generates two FWMs at +/- Δf from the idler, with the same polarization
- However, in actual optical fiber,
  - The fluctuation of zero dispersion frequency (ZDF) significantly reduces FWM efficiency
  - If signal separation is too large, FWM efficiency significantly drops (FWM bandwidth, for ex., 16 nm)
  - Polarization angle of signals at different frequencies is gradually changed due to polarization mode dispersion (PMD)
- Therefore, statistical analysis is important

How to Mitigate FWM: "Polarization arrangement"

- **"SPPS"** polarization arrangement
  - Proposed by Liu *at al.*, in IEEE 802.3df Plenary Meeting, July, 2022.
  - Inner two signals has orthogonal polarization to the outer two signals.
  - FWMs overlapping on the signal frequencies has the orthogonal polarization with the signal, thus, signal degradation can be suppressed.

  <Pros>
  - No extra bandwidth
  - FWM degradation can be completely suppressed even at the worst case fiber with very high FWM efficiency (ZDF matching)

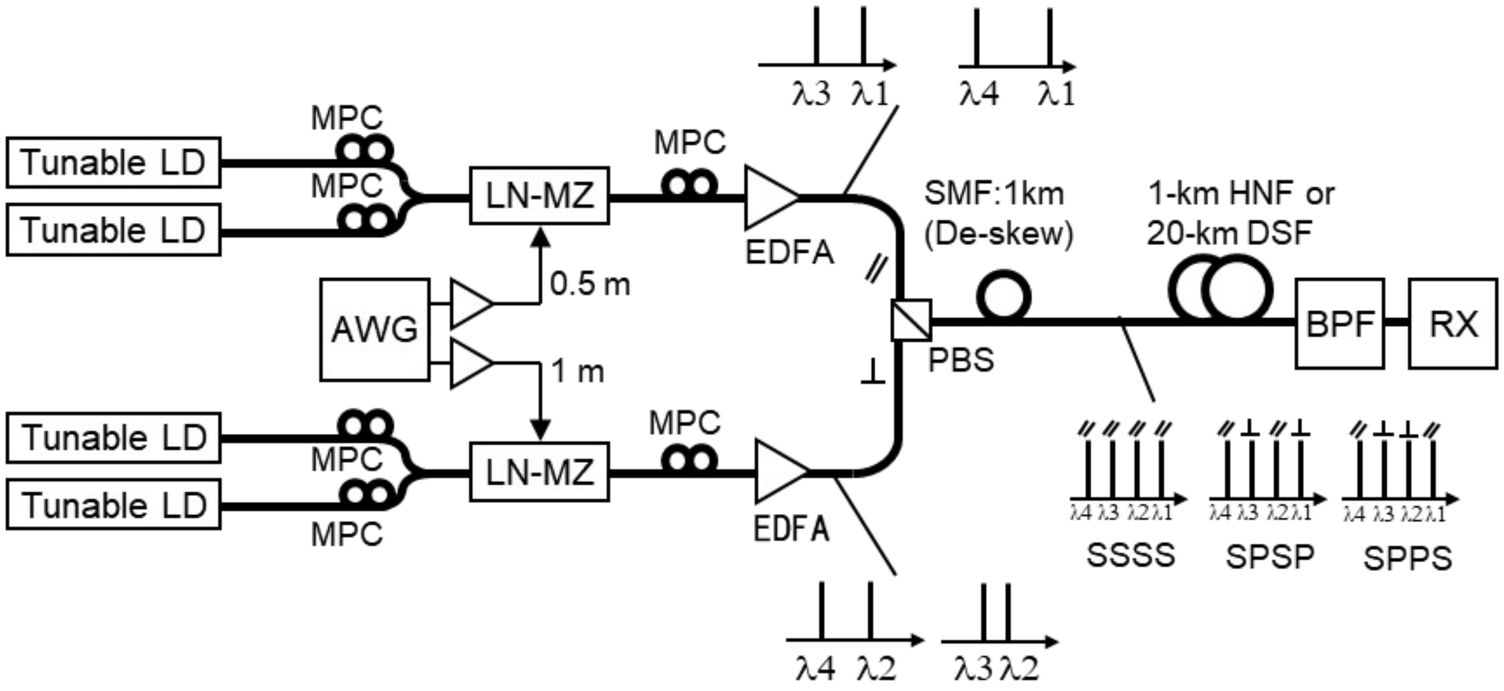
...But
- Does it really work?
- Is it really effective in actual fiber with PMD?



SPPS case

Demonstration Experiments

- We carried out FWM suppression experiment in 1.5-μm band, since it is preferable for FWM generation
  – EDFA enables higher fiber input power
  – HNF (highly non-linear fiber) can be used for emulating worst-case fiber

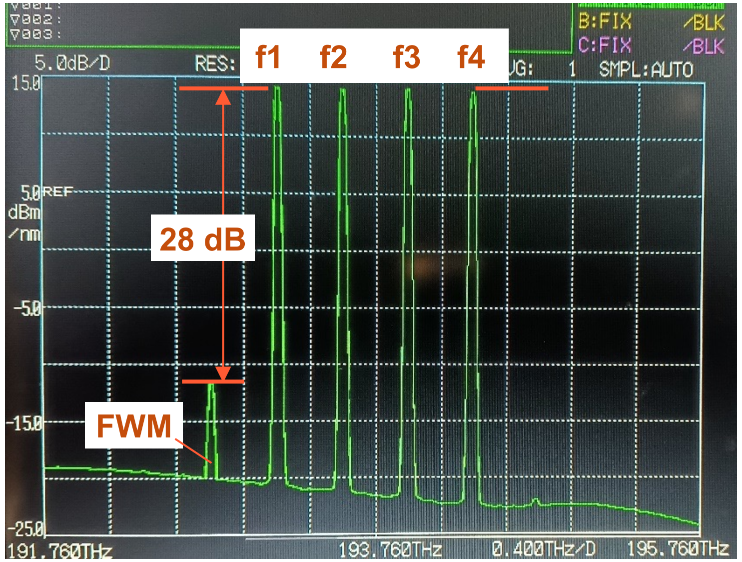


Experimental setup

- ✓ Tx 1.5-μm 4-wavelength with 400 GHz (3.2 nm) spacings
- ✓ IM/DD 40-GBaud PAM4 generated by LN-MZ modulator (Extinction ratio ~5 dB)
- ✓ 1-km SMF is used to de-correlate signal patterns modulated by a same modulator
- ✓ Fiber input power is set to +6 dBm/ch.
- ✓ 1-km HNF: loss 0.4dB/km, non-linear coefficient γ = 16 /W/km, D_0=1547 nm
- ✓ 20-km dispersion shifted fiber (DSF): loss 0.2 dB/km, A_{eff} = 60 μm

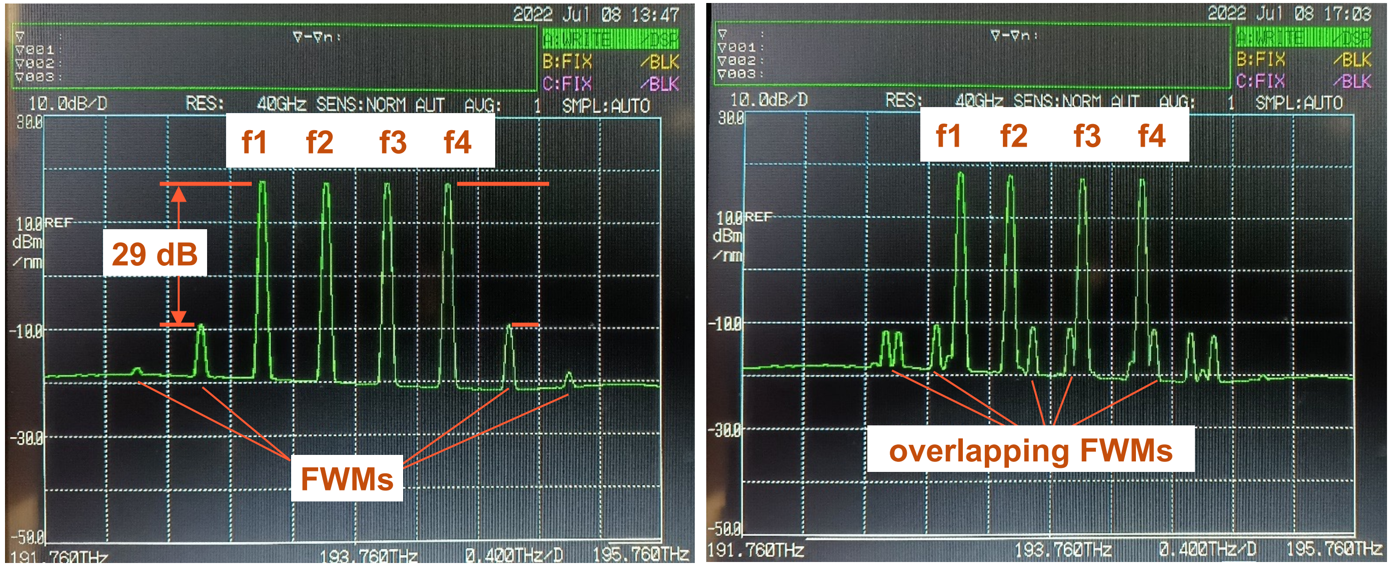
Results

- The 20-km DSF used in the experiment is the worst one out of 13 spools. Other ones show very small FWM or no trace of it
- Relative FWM power is -29 dB for HNF, -28 dB for DSF case with the fiber input power of 6 dBm/ch
- Example FWM spectra ("**SPSP**" case, same in "**SPPS**" case)



FWM generation in 20-km DSF (5dB/div)

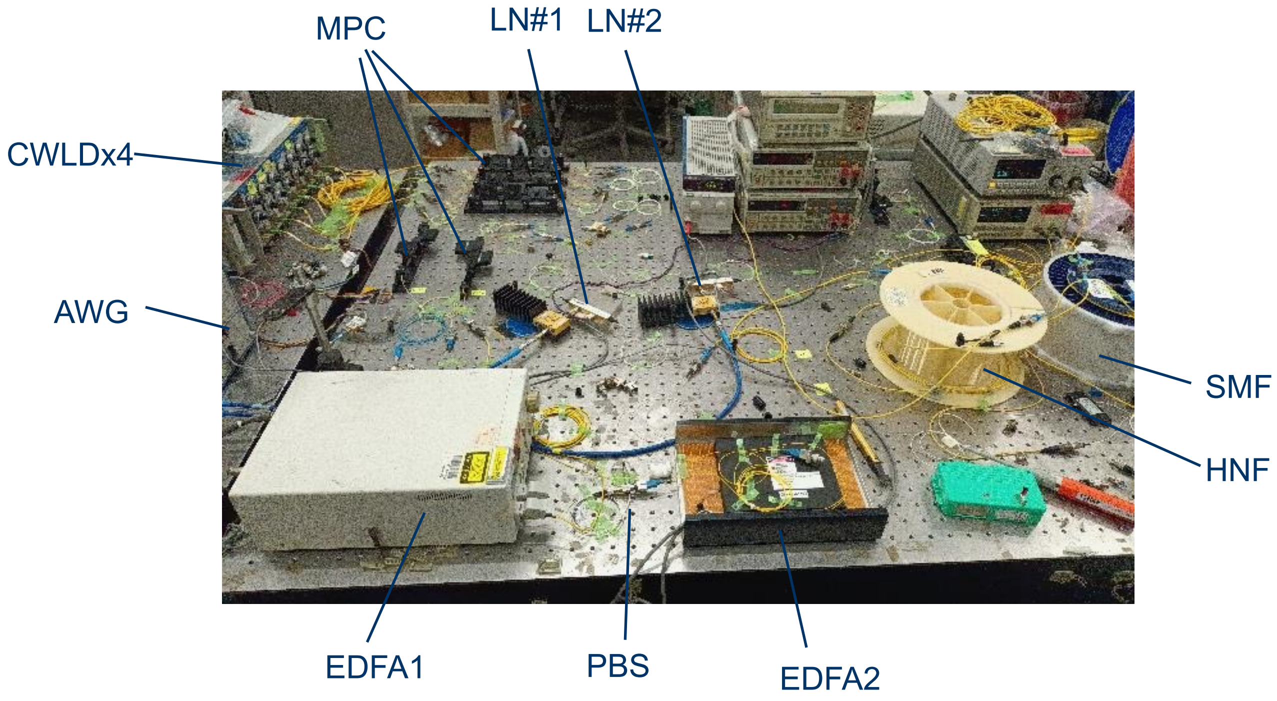
(Ch2 at f2 is slightly shifted)



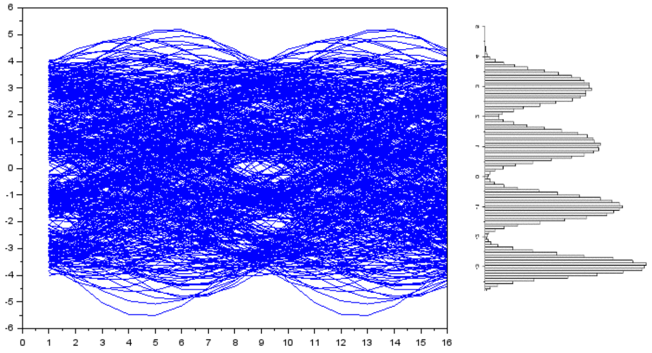
FWM generation in HNF (10dB/div)

Experimental Setup and Example of Received Waveforms

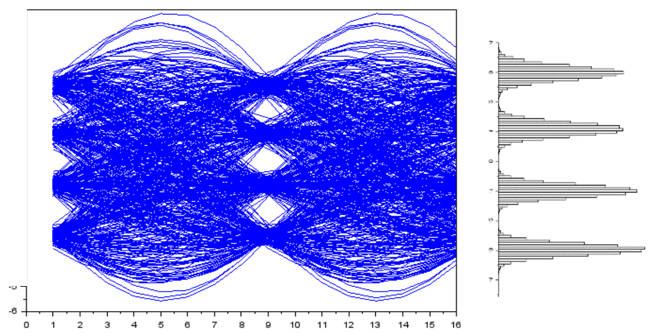
- Photo of the experimental setup



- Received waveforms
  - In SPSP case, eye-opening is lost by strong FWM crosstalk
  - In SPPS case, clear eye-opening is obtained even with -28 dB FWM crosstalk



HNF1km SPSP (Ch1)



HNF1km SPPS (Ch1)

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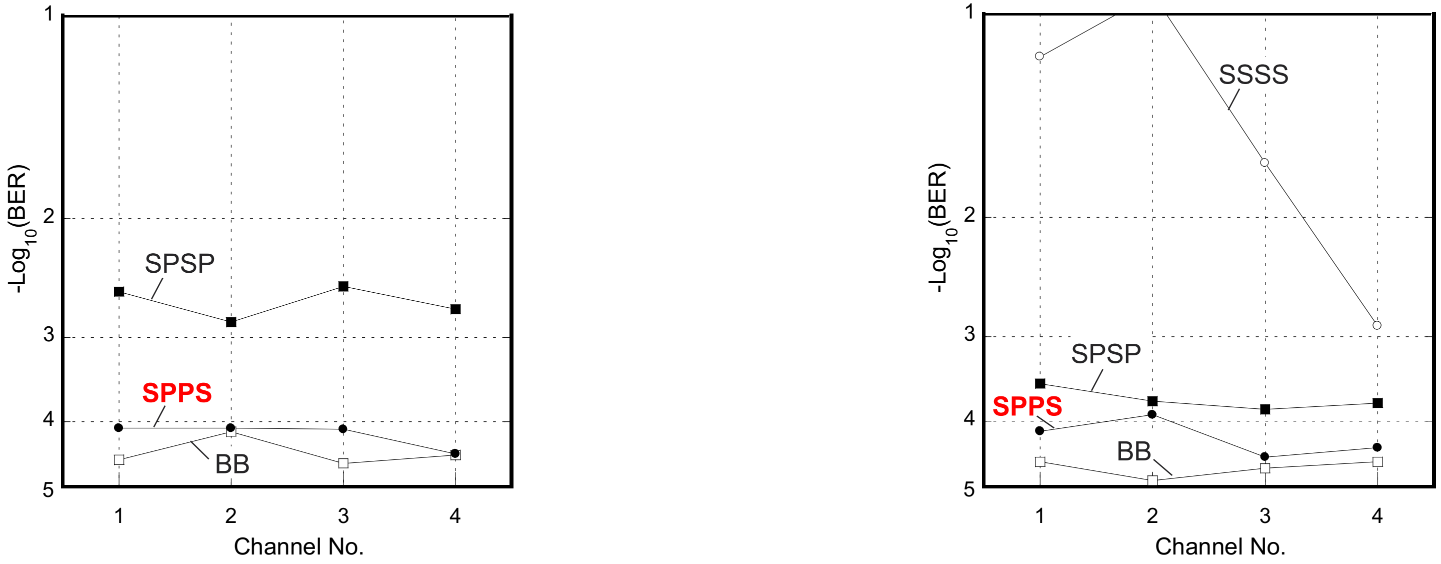
Results: Measured BER Performance for HNF and DSF Cases

1. 1-km HNF (worst case fiber with wide FWM bandwidth and small PMD)
   - "**SPPS**" arrangement showed good BER<1E-4 with slight degradation from back-to-back (no-fiber) case
   - Conventional polarization interleaving "**SPSP**" was degraded to BER>1E-3
2. 20-km DSF case (FWM with PMD)
   - The FWM suppression effect of "**SPPS**" was still valid in actual fiber with PMD
   - The BER of "**SPSP**" was rather improved possibly by PMD, maybe SPSP is not the best polarization arrangement



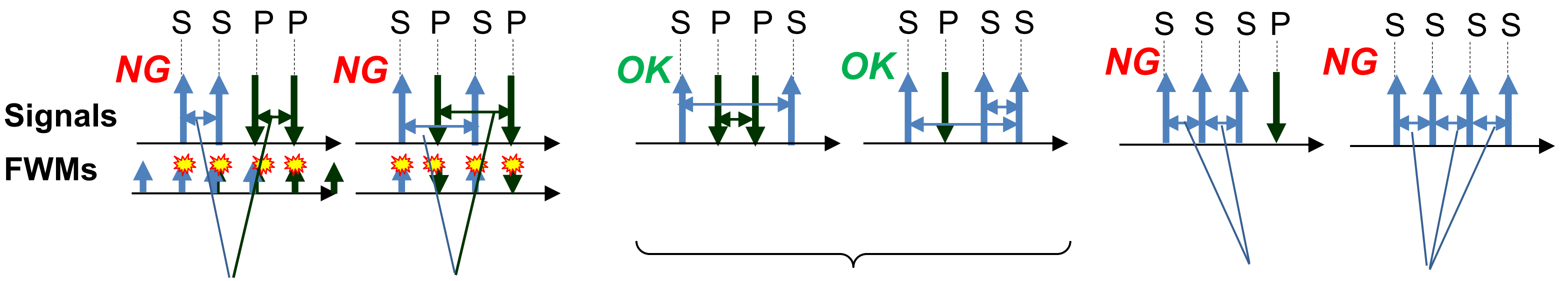
(1) HNF 1km (2) DSF 20km

Experimental BER performance of 4 WDM 40 GBaud PAM-4 transmission

Rule of Thumb for FWM Suppression

- In assignment of M IM/DD signals on successive N equi-spaced frequency grid, the general rule of FWM suppression are:
  1. Assign each signals into either two mutually-orthogonal polarization groups S or P
  2. No two waves in the same polarization groups (S or P) has the same frequency spacing
     (= Unequal spacing arrangement in S and P, respectively)
  3. No two waves from S and two waves from P has the same frequency spacing

(Ex.1) N=4/M=4 case: Only **SPPS** and **SPSS** satisfy the rule.



Fail, due to same spacings in S and P group

OK, satisfy all the rules above

Fail, due to the same spacings in the same polarization group

Rule of Thumb for FWM Suppression (cont.)

(Ex.2) N=5/M=4 with one guard grid (G)

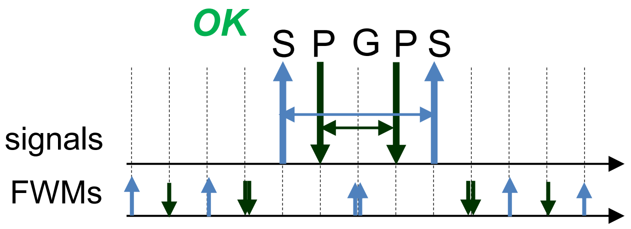


Fig. SPGPS case

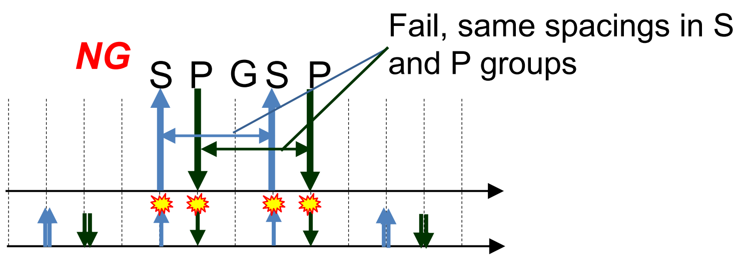


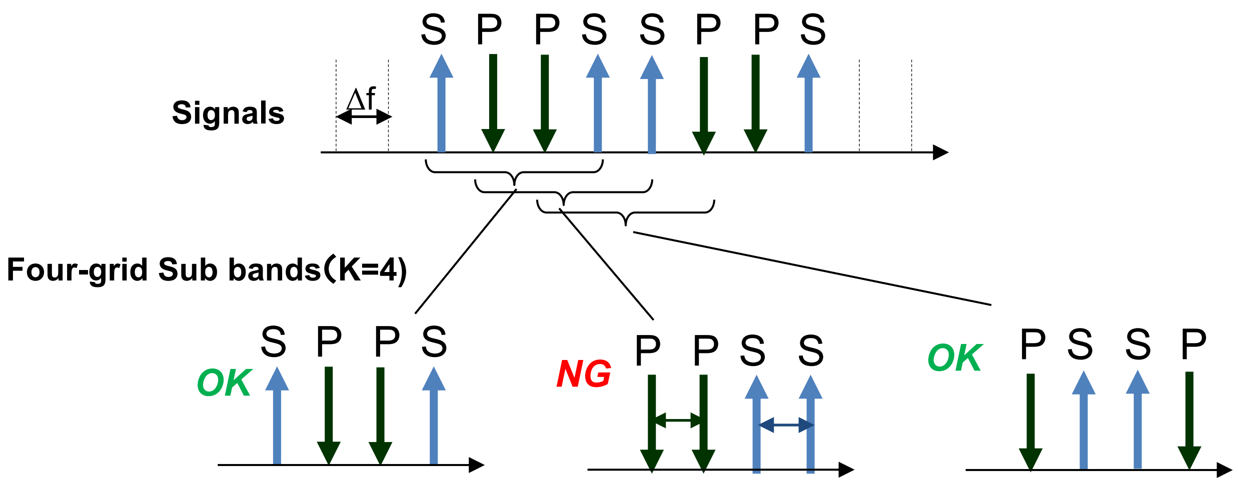
Fig. SPGSP case

"SPGPS" seems to have extra benefit of having no FWMs on the same frequency with signals at all, which may further enhance FWM crosstalk suppression

Extension to Eight Waves (M=8)

- Without guard grid (N=M), maximum N(or M) that satisfies the FWM rule is 4
- Fully satisfying the FWM rule for M=8 with guard band requires a quite wide wavelength range
- Introduction of "sub-band (K-successive grid, K<N)" seems to be reasonable
  - FWM is locally-suppressed at any sub-bands over the wavelength band.
  - "Sub-band width KΔf" > "FWM bandwidth" seems to assure FWM suppression

(Ex.3) **SPPSSPPS** (N=M=8) ... **NG**, some sub-bands are weak to FWM, even K=4.



Proposal for Extension to Eight Waves (M=8)

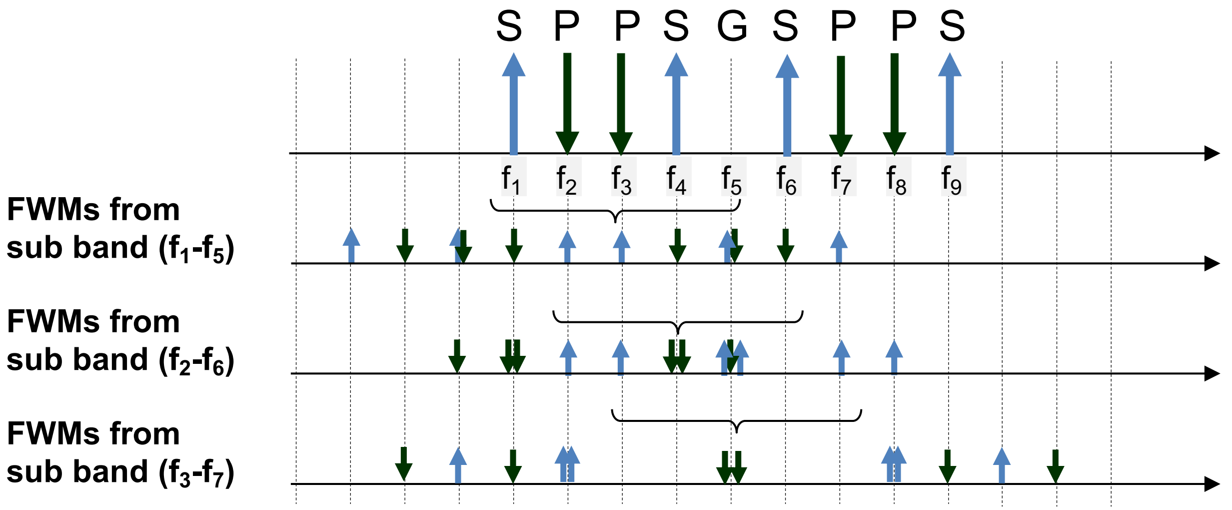
- "**SPPSGSPPS**" (N=9, M=8) is a very special case for FWM suppression

1. Up to any K=5 sub-bands, the FWM suppression rule is satisfied.

   SPPSG: OK, **PPSGS**: OK, **PSGSP**: OK

   ... If Δf=800 GHz, K=5 sub-band width is 4 THz(~22 nm), which may be wider than the FWM bandwidth of the worst case fiber (16 nm).

2. All the FWM components of any K=5 sub-bands overlapping to any signals has orthogonal polarization to it even outside of the sub-bands.



3. It can be further extended limitlessly, like "**SPPSGSPPSGSPPSG....**"

Summary

- Effectiveness of “SPPS” polarization arrangement for suppressing Four Wave Mixing (FWM) effect is experimentally verified
- Introduced simple "rule of thumb for FWM Suppression" and the concept of sub-band
- We propose "**SPPSGSPPS**" polarization arrangement for 8-wavelength IM/DD PAM system (G: Guard grid), which can suppress FWM degradation for any sub bands up to five-grid width.
- We will perform numerical simulation to confirm its effectiveness

Thank you

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