Photonic Signal Processing (PSP) of Microwave Signals

Introduction

- Fundamental discrete-time signal processing

\[ y(t) = \sum_{n=0}^{N} W_n x(t - nT) \]

- Fundamental functions
  - Sampling
  - Delay
  - Weight
  - Sum

\[ W_n = n_{th} \text{ tap weight} \]
\[ N = \text{the number of taps} \]
\[ T = \text{sampling period} \]

< Basic delay-line processor structure >
Introduction

- **Photonic Signal Processing (PSP)**
  - Direct process of high bandwidth signals in the optical domain
  - Overcome the inherent bottlenecks caused by limited sampling speed in conventional electrical signal processing

- **Optical delay medium**
  - Significantly low loss
  - Independent loss of modulating frequency
  - Low and controllable dispersion

- **Advantages**
  - Inherent speed
  - Parallel signal processing capability
  - Low-loss delay line
  - Very high sampling rate
  - EMI immunity

<Propagation loss characteristics of various delay media>
Introduction

- Sampling operations in PSP

Mach–Zehnder based

**Discrete grating arrays**

- Grating reflectivity: tap weight
- Grating space: sampling time
- Grating pitch: interaction wavelength
- Time delay Tuning by changing the wavelength

**Superposed arrays**

- Sampling time $T \sim 10$ ps, $f_{sa} = 100$ GHz
- Sampling time $T \sim 1$ ps, $f_{sa} = 1$ THz

AWG based

< Bragg grating based sampling >

- Grating reflectivity: tap weight
- Grating space: sampling time
- Grating pitch: interaction wavelength
- Time delay Tuning by changing the wavelength
Microwave Photonic Filters

A. Band-pass Filter (BPF)

Key parameters and requirements

- High Q factor \( (\frac{f_0}{B}) \)
- High stopband attenuation, \( A \)
- Skirt selectivity
- Shape factor = \( S/B \)

High rejection of unwanted frequencies adjacent to the desired signal frequency

A : stopband attenuation
B : 3dB bandwidth
S : 40dB bandwidth

The general frequency response of BPF
A. Band-pass Filter (BPF)

- Single cavity fiber-based BPF

\[ H(z) = \frac{g(1 - R_1)(1 - R_2)}{1 - g^2 R_1 R_2 z^{-1}} \]

- Limitation
  - Gradual fall-off characteristic
  - Cannot control the shape factor

- Solution
  - Dual cavity parallel fiber based BPF
Microwave Photonic Filters

A. Band-pass Filters

- Dual cavity fiber-based BPF

- Based on offset gain cavities to control the poles and stopband attenuation
- Center frequency: upper arm has higher gain and sharper response
- Far away from the center frequency: nearly identical response of both arms
- High stopband attenuation and skirt selectivity by subtraction process

![Diagram of dual cavity fiber-based BPF with EDFA and 980 nm pump laser](image)

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Frequency response of dual cavity BPF
B. Interference Mitigation Filters (=Notch Filter)

- Requirements: Narrow stopband & flat wide pass band

- Use multiple photonic band-pass filters
- Notch frequency: controlled by cavity length \( L \) \( f_0 = \frac{1}{T} = \frac{c}{2nL} \)
- Band pass frequency is slightly detuned from notch frequency \( [f_0] \) by offset cavity lengths \( [\Delta L] \)
- 3dB bandwidth: controlled by cavity length difference and EDFA gain
Microwave Photonic Filters

C. Filters with large FSR

- Discrete-time signal processing
  - Limited useful frequency range by periodic response
  - Need to suppress the recursive responses to increase the useful operation bandwidth

1. Non-uniform wavelength spacing based filter (BPF)

- Non-uniform time delays between taps
- Increase FSR

< Vernier effect >
Microwave Photonic Filters

C. Filters with high FSR

② notch filter with large FSR

- Based on multiple wavelengths, cavities and unbalanced delay lines
- Cascade of unbalanced delay lines: series of notches that suppress several harmonics

\[
\text{All pass} - (\text{BPF} + \text{Notch filter}) = \text{Notch filter with large FSR}
\]
Arbitrary Waveform Generation

- Photonic AWG
  - Overcome the limited speed and linearity of electronic device
  - Based on sampling and delay line technique

Delay–Attenuation–Coupling (DAC) process to increase sampling speed
Signal Correlators

- Programmable optical code correlation
  - Based on programmable gratings

- Center wavelength control
  - Determine 1: (reflection), 0: (no reflection)

\[ R(\tau) = \int_{-\infty}^{\infty} s(t)f(t-\tau)dt \]

- \( s(t) = \text{incoming code sequence} \)
- \( f(t) = \text{stored impulse response} \)

- Arbitrary sequences can be stored by tuning the gratings
- \( s(t) = f(t) \), autocorrelation output
- \( s(t) \neq f(t) \), cross-correlation output
PSP without phase noise limitations

A. WDM PSP
   - Use multiple wavelengths
   - Eliminating coherence problem

   - Bipolar tap using dual–output EOM
     - Dual–output EOM outputs have opposite phase
     - Negative tap: high resolution filter
PSP without phase noise limitations

B. PSP with Tap polarization control
   - Use two orthogonal polarizations
   - Require only a single laser source

C. Double-pass-modulation based notch filter
   - Second modulation: produce notches at all frequencies where the remodulation is an odd integer multiple of 180° phase difference to the returned modulated RF signal
   - L: determine notch frequency
   - Only a single optical path: no coherent interference effect
PSP without phase noise limitations

D. Multi-Tap coherence free processors

- Use frequency shifting loop
- Recirculation: imposes frequency shift and time delay
- Phase induced intensity noise (PIIN) appears at the beat frequency, not at the baseband
- PIIN is automatically filtered out by PD bandwidth

\[ f_s > 3 \times f_m \]
Summary

- Photonic signal processing
  - Direct process of high bandwidth signals in the optical domain
  - Advantages
    - Parallel signal processing capability
    - Low-loss delay line
    - Very high sampling rate
    - EMI immunity

- Several photonic signal processors
  - Microwave photonic filters
  - Arbitrary waveform generation
  - Signal correlators

- Coherence free solutions
  - WDM solution with bipolar weight
  - Polarization solution
  - Double-pass-modulation
  - Frequency shifting loop system
Thank you for listening

Q&A