Conversion between Optical ASK and Optical FSK
Using Nonlinear Dynamics of Semiconductor Lasers

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Outline

• Optical Modulation Formats
  - format categories and types
  - format conversion schemes

• Proposed Method
  - nonlinear laser dynamics
  - static characteristics
  - dynamical characteristics

• Summary

Various Optical Modulation Formats

• Amplitude-Shift Keying (ASK)
  - on-off keying (OOK): includes RZ & NRZ, most commonly used now
    simple transmitter/receiver, low spectral efficiency, short-range communication
  - CSRZ, CRZ, DB, AMI, VSB, SSB …

• Phase-Shift Keying (PSK)
  - binary PSK (BPSK), quadrature PSK (QPSK), multi-level PSK
  - differential BPSK (DPSK), differential QPSK (DQPSK)

• Frequency-Shift Keying (FSK)
  - wideband FSK
  - narrowband FSK

Some Proposed Format Conversion Schemes

• OOK-to-PSK conversion
  - optical semiconductor amplifier based on cross phase modulation effect
    W. Hong et al., Optics Express, vol. 15, pp. 18357, 2007
  - optical fiber based on cross phase modulation effect
    M. Mishina et al., Optics Express, vol. 15, pp. 8444, 2007
    W. Astar et al., Optics Express, vol. 16, pp. 12039, 2008

• PSK-to-OOK conversion
  - semiconductor laser based on injection locking-unlocking effect

• FSK-to-PSK conversion
  - Mach-Zehnder modulator based on double-sideband suppressed-carrier scheme
    T. Kawanishi et al., Optics Express, vol. 13, pp. 8038, 2005

formats other than OOK are proposed for various purposes and considerations even though they are more complex in system configuration and operation, such as, high spectral efficiency, long-range communication, more robust to noise, dispersion, and nonlinearity etc.
Semiconductor Laser Dynamics: Before Injection

- Laser output: continuous wave (before injection)
- laser output: continuous wave
- $f_r$: relaxation resonance frequency
- $f_{cr} = f_2$
- $f_1, f_r$ (cavity resonance (before injection))

Semiconductor Laser Dynamics: After Injection

- Optical injection
- Attempts to pull laser oscillation toward $f_1$ (Injection-pulling-effect)
- cavity resonance (after injection)
- cavity resonance
- $f_r: f_1, f_2, f_{cr}$
- $f_1 = \frac{\Gamma}{4\pi} \ln \left( \frac{g - g_f}{\Gamma} \right)$
- linewidth enhancement factor
- Intensity and Frequency are both changed
- Change relative injection frequency
- Intensity and Frequency are both changed

Proposed Scheme: Period-One (P1) Dynamics

- Optical injection
- Laser output: periodic oscillation (after injection)
- $f_1, f_3, f_2, f_{cr}, f_4, f_r$
- Laser Diode
- Laser Diode
- Laser Diode
- Laser Diode
- Laser Diode
Proposed Scheme: Period-One (P1) Dynamics

Laser Diode

optical injection

f_1, f_2

Change Injection Level

Intensity and Frequency are both changed

laser output: periodic oscillation (after injection)

f_3, f_4, f_5, f_6

Numerical Result of Static Characteristics (1)

changes in injection level lead to changes in output frequency and intensity

Numerical Result of Static Characteristics (2)

changes in injection frequency lead to changes in output frequency and intensity

Numerical Result of Dynamical Characteristics (3)

output modulation depth depends on injection condition monotonically and continuously
Numerical Result of Dynamical Characteristics (4)

Output modulation depth depends on injection condition monotonically and continuously.

Numerical Result of Bit-Error Ratio & Eye Diagram (1)

Similar observations are found for other injection conditions.

Numerical Result of Bit-Error Ratio & Eye Diagram (2)

Similar observations are found for other injection conditions.

Experimental Set-up of ASK to FSK Format Conversion

TL: Tunable Laser
EM: External modulator
LD: Laser Diode
PD: Photo detector
BERT: Bit Error Rate Tester
TL: Tunable Laser
EM: External modulator
LD: Laser Diode
PD: Photo detector
BERT: Bit Error Rate Tester
OSA: Optical Spectrum Analyzer
PSA: Power Spectrum Analyzer
OSA: Optical Spectrum Analyzer
PSA: Power Spectrum Analyzer
TL: Tunable Laser
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Experimental Set-up of ASK to FSK Format Conversion

**TL**: Tunable Laser  
**EM**: External modulator  
**LD**: Laser Diode  
**PD**: Photo detector  

**BERT (2.5Gb/sec)**

**ASK generation Unit**  
**ASK to FSK converter**  
**Signal analysis**

Experimental Result of ASK to FSK Format Conversion (1)

Free-running Laser Diode  
Incoming signal  
Period-one dynamics

Experimental Result of ASK to FSK Format Conversion (2)

Free-running Laser Diode  
Incoming signal  
Period-one dynamics

19.53GHz
Experimental Result of ASK to FSK Format Conversion (3)

Free-running Laser Diode
Incoming signal
Period-one dynamics

39.67 GHz

Experimental Result of ASK to FSK Format Conversion (4)

Free-running Laser Diode
Incoming signal
Period-one dynamics (With DATA)

Experimental Result of ASK to FSK Format Conversion (5)

Filter
Free-running Laser Diode
Incoming signal
Period-one dynamics (With DATA)

Experimental Result of ASK to FSK Format Conversion (6)

111
0000000

The original data is “0000000111” and the data rate is 2.5Gbits/s.
The original data is "0000000111" and the data rate is 2.5Gbits/s.

Summary

- All-optical modulation format conversion between ASK and FSK using period-one nonlinear dynamics in semiconductor lasers is proposed and demonstrated

- Characteristics:
  - only a typical semiconductor laser is required as the conversion unit
  - bi-directional (ASK-to-FSK, FSK-to-ASK) format conversion is feasible
  - large dynamic range for input modulation depth
  - output modulation depth can be adjusted by adopting different spectral components or different injection conditions
  - simultaneous frequency shift of optical carrier occurs and can be adjusted via injection condition
    (no such frequency shift for FSK-to-ASK conversion is possible)