南京航空航天大學
NANJING UNIVERSITY OF AERONAUTICS AND ASTRONAUTICS

Lecture #05

Applications

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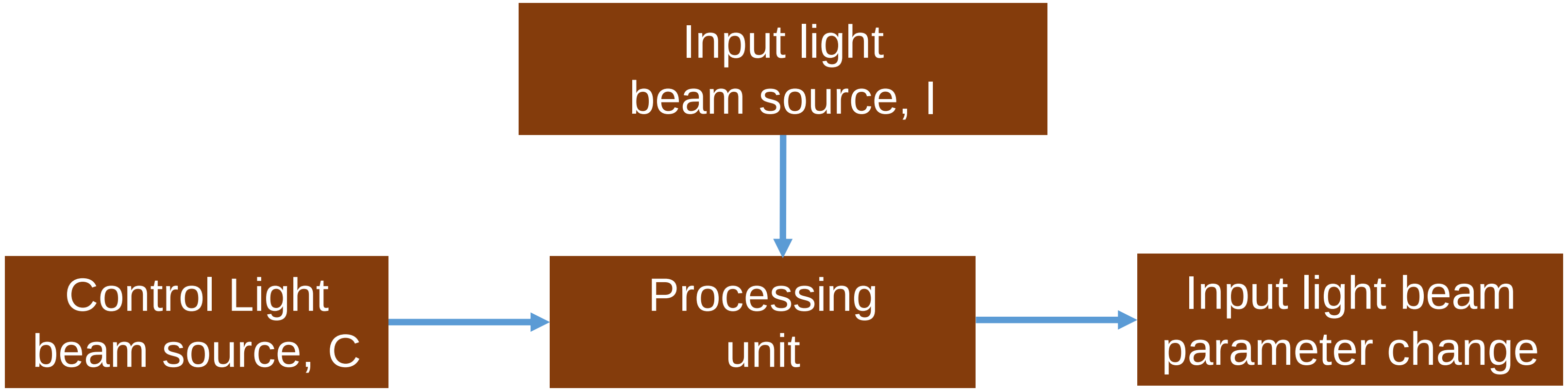
Applications in Microwave Photonics

Introduction



Basic block diagram of optical signal processing

- In the block diagram have two light beam sources, one is input light source, I, and control beam source, C.
- With the interaction of input beam with control beam C, some of the parameter of input light beam, I, can be changed.
- The parameters may be wavelength, amplitude and phase. By changing the parameter of input beams, the output can be function as wavelength converter, switching, modulation and Others.

Introduction

control the different parameter of the light beam by another beams /different light beams interaction.

Advantages

- High bandwidth
- High spectral and spatial coherence
- RF interference free
- Robustness to the cosmic radiations
- Low distortions in signal distribution

- Applications and related projects
  - Ultra-fast interconnection optical networks (MUFINS, LASAGNE, EUROFOS in Europe, NEDO in Japan)
  - Network security (Optical firewall –WISDOM in Europe)
  - Optical Computing (Lincoln Laboratory-MIT)
  - Microwave Optics & Low phase noise radar transmissions
  - Sensors in hostile surroundings
  - Grid Computing
  - Medical applications
  - Biophotonics and Spectrograph
  - Material characterization and applications in space capsules (NASA)
  - Interference Mitigations

Injection locking: Operating Principle

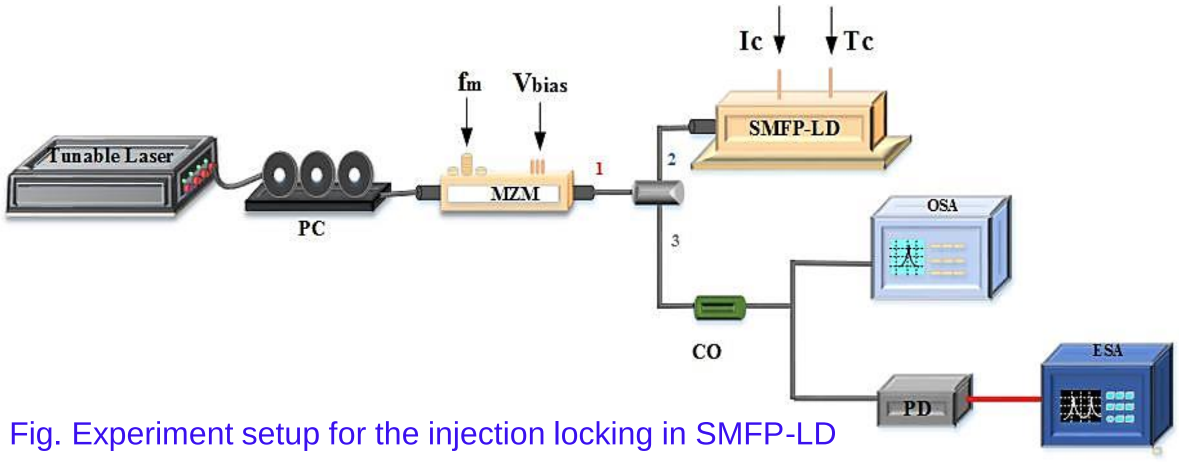
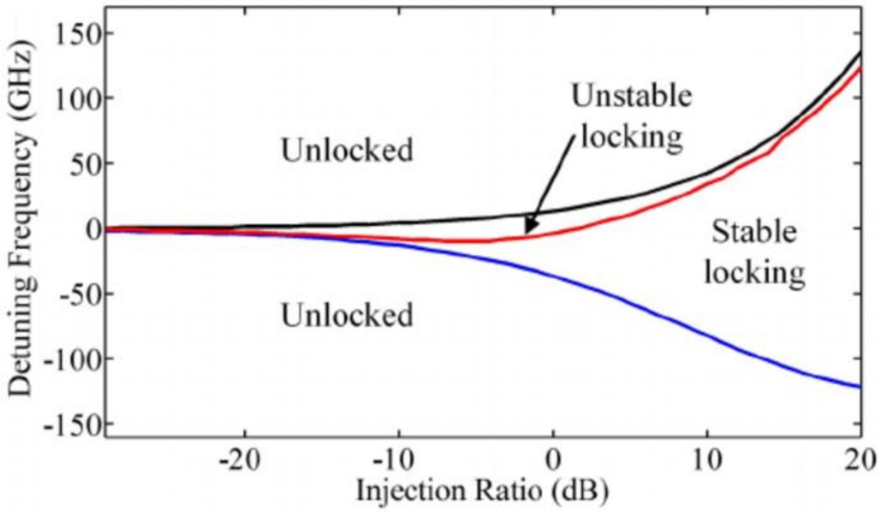


Fig. Experiment setup for the injection locking in SMFP-LD



$$\frac{dE_s(t)}{dt} = \frac{1}{2}(1 - i\alpha)G_n(n(t) - n_{th})E_s(t) + \frac{\kappa_{inj}}{\tau_{in}}E_m(t)e^{-i\Delta\omega t}$$

External injection

$$\frac{dn(t)}{dt} = \frac{J}{ed} - \frac{n(t)}{\tau_s} - G_n\{n(t) - n_0\}E^2(t)$$

- In PIL, 2 states: Strongly Injection Locking & Weakly Injection Locking
- In NIL, 4 states : Strongly Injection Locking, Moderate Injection Locking & Weakly Injection Locking

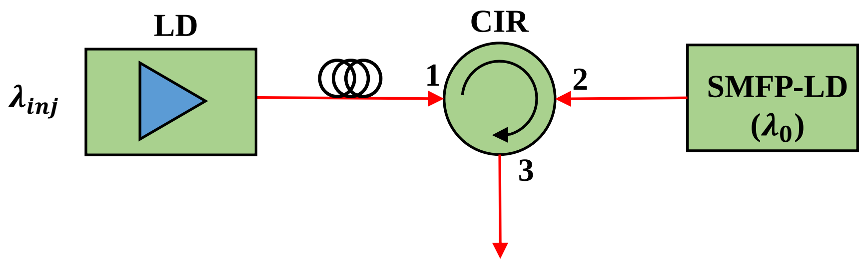
Deciding parameters to obtain the injection locking

- Wavelength Detuning
- Input Injected Beam Power
- Polarization state

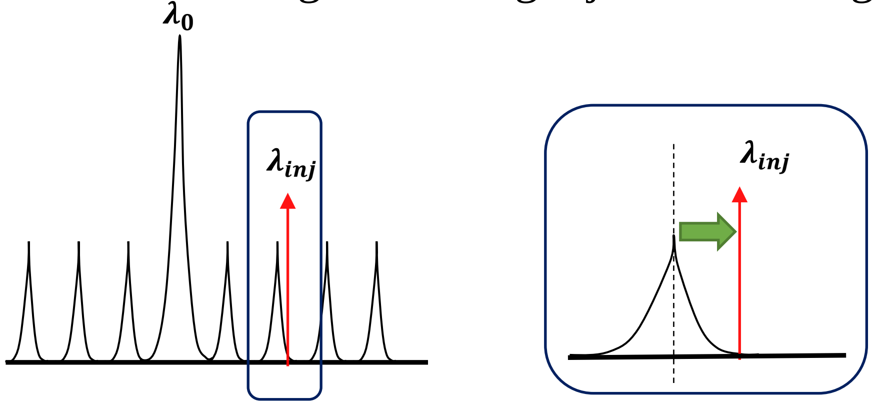
Ref: Bikash Nakarmi, T.Q.Hoai, Y.H.Won, Xuping Zhang, IEEE Photonics Journal, June 2014.,

Wang, Pet. Al, , 2015. Frequency tunable optoelectronic oscillator based on a directly modulated DFB semiconductor laser under optical injection. *Optics express*, *23*(16), pp.20450-20458

LD: Operating Principle

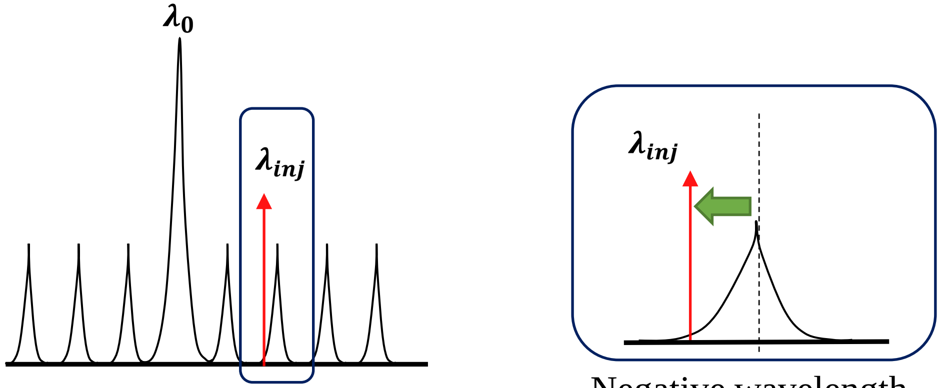


A) Positive wavelength detuning injection locking



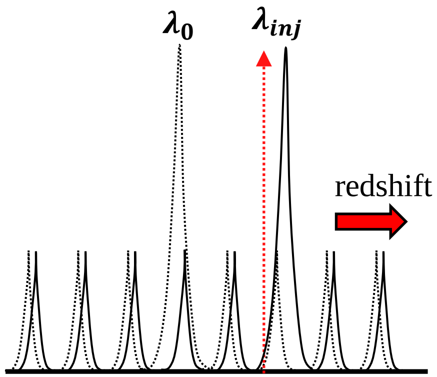
Positive wavelength Detuning

B-1) Negative wavelength detuning injection locking :Period-one (P1) oscillation

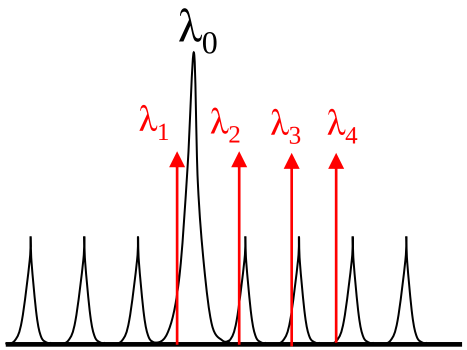


Negative wavelength Detuning

B-2) P1 with redshift



C) Multi input injection locking



SMFP-LD: Injection Locking (PIL & NIL)

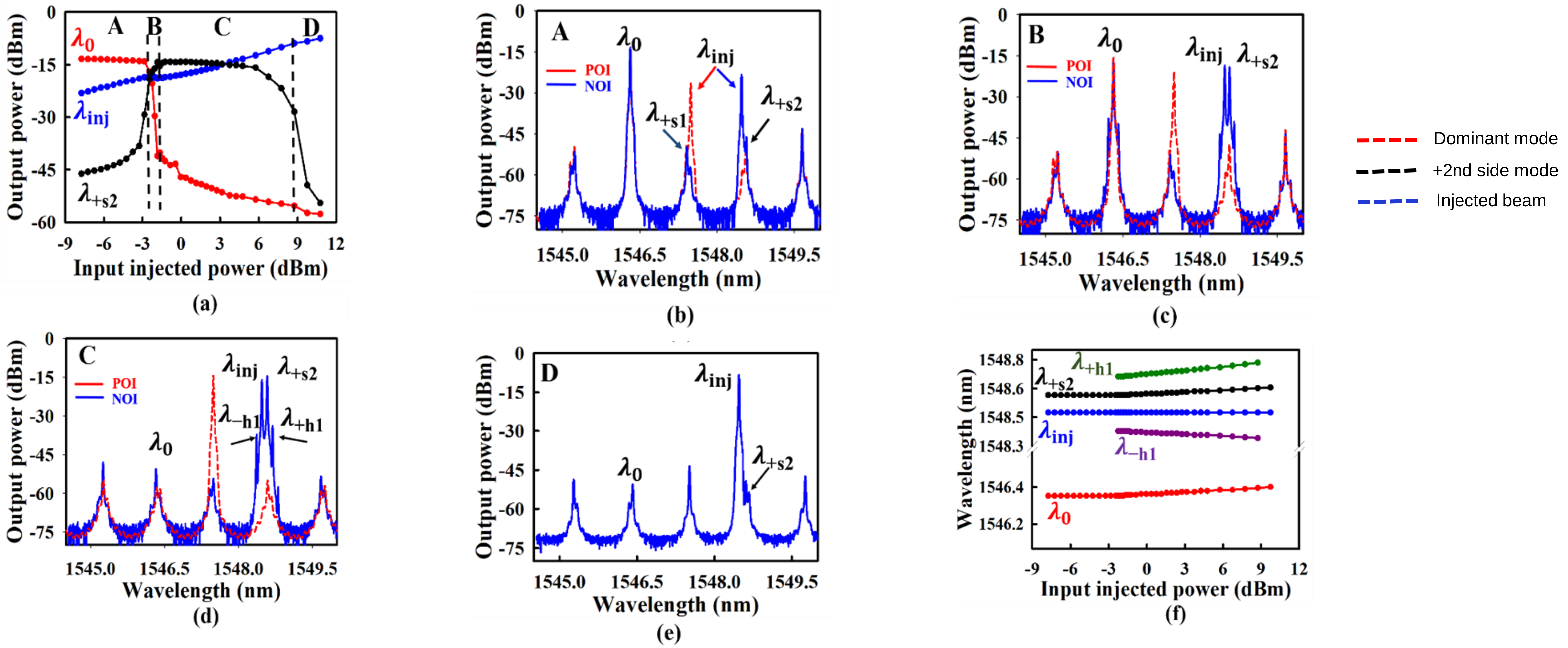


Fig. Experiment analysis of the NOI and POI in SMFP-LD: (a) output power variation of different modes (b) weak injection (c) moderate injection (d) strong injection (e) ultrahigh injection (f) wavelength variation.

Ref: H. Chen, B. Nakarmi, M. Rakib Uddin, and S. L. Pan. *IEEE Photonics Journal*,2019

SMFP-LD: Optical Bistability

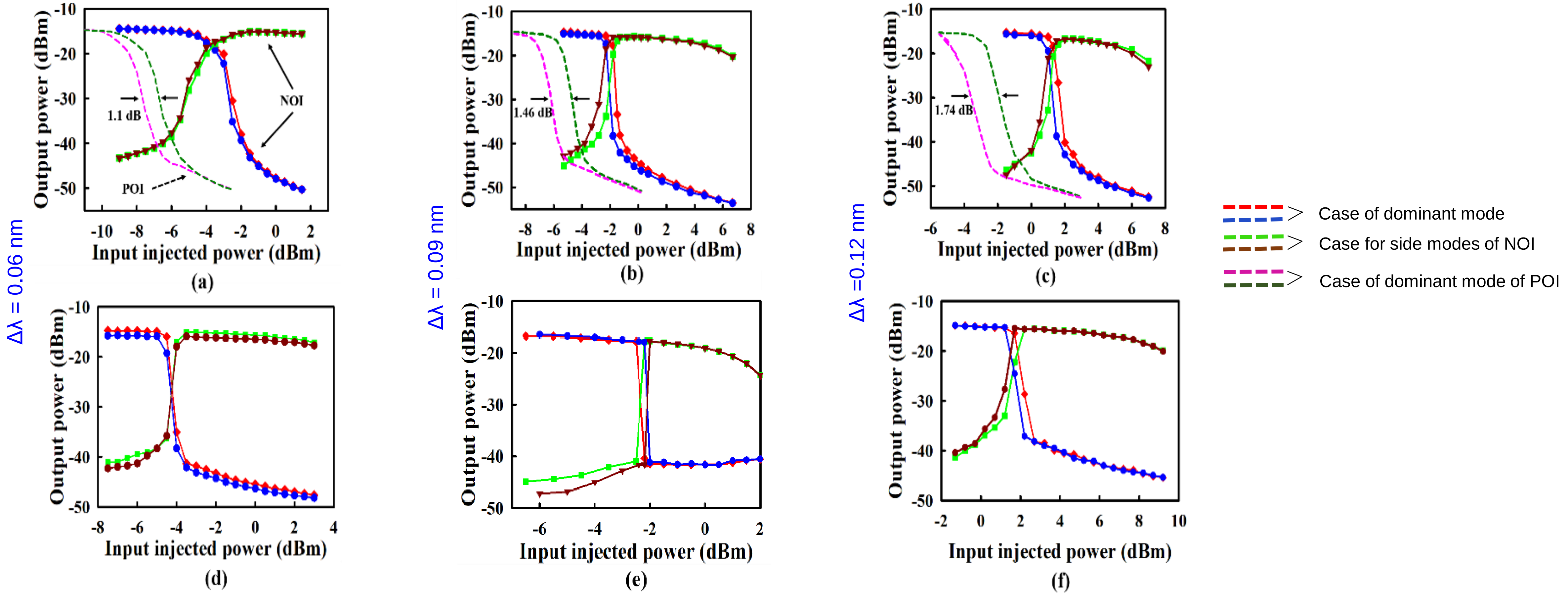


Fig. Bistability properties analysis of the POI and NOI in the SMFP-LD (a)(b)(c) injected to λ+s1; (d)(e)(f) injected to λ+s2.

Ref: H. Chen, B. Nakarmi, M. Rakib Uddin, and S. L. Pan. *IEEE Photonics Journal*,2019

Microwave Photonics: Introduction

- Microwave Photonics introduced in 1991
- shortest wavelength region of Radio spectrum and a part of EM spectrum

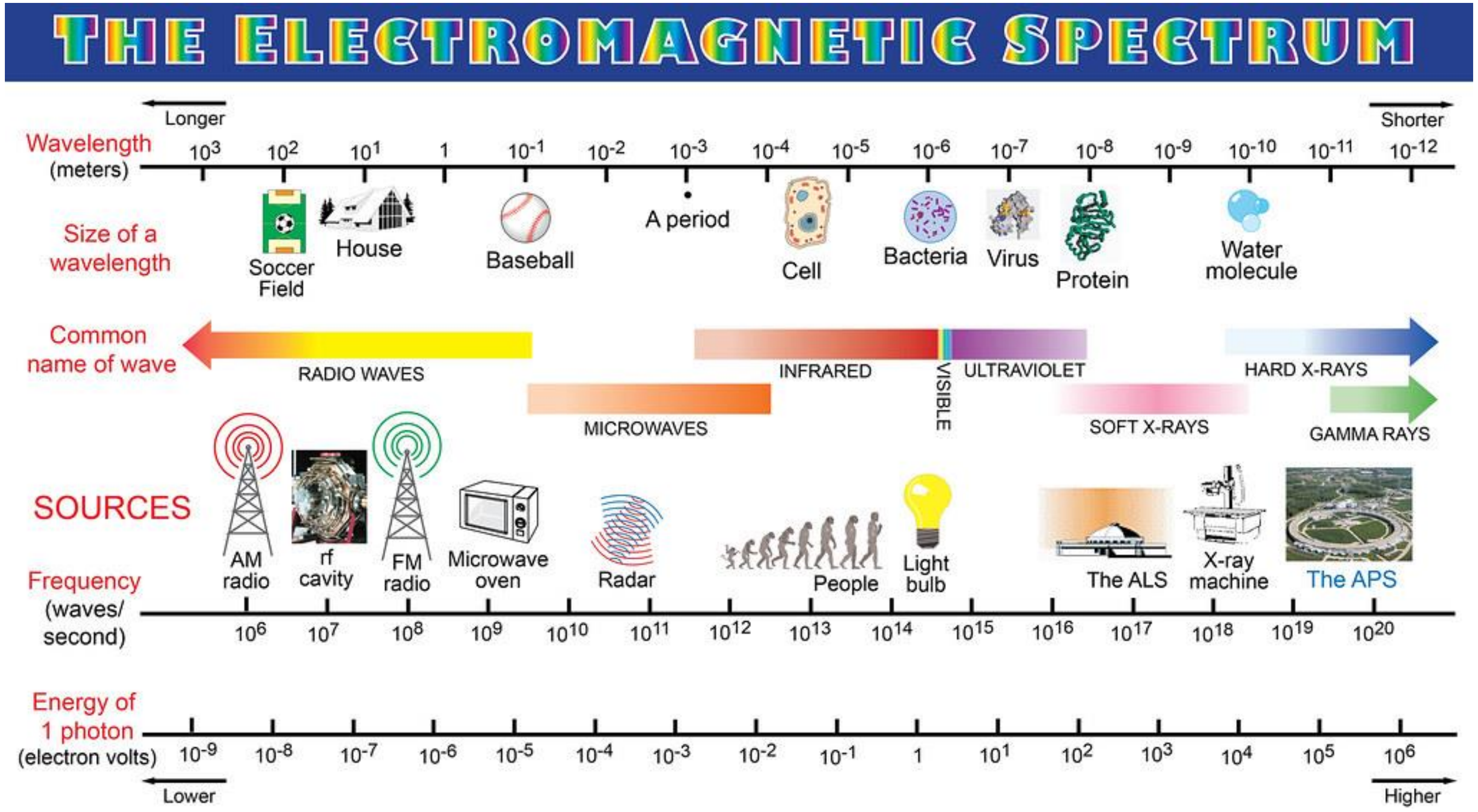


Fig. Electromagnetic Spectrum

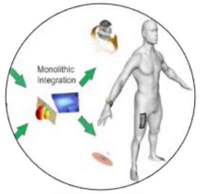
Advantages

- Large Bandwidths and higher sped
- Improved Directive, smaller antenna size
- Low power requirements are pretty low for Tx and Rx at microwave frequencies
- Smaller antenna size

Microwave Photonics: Introduction

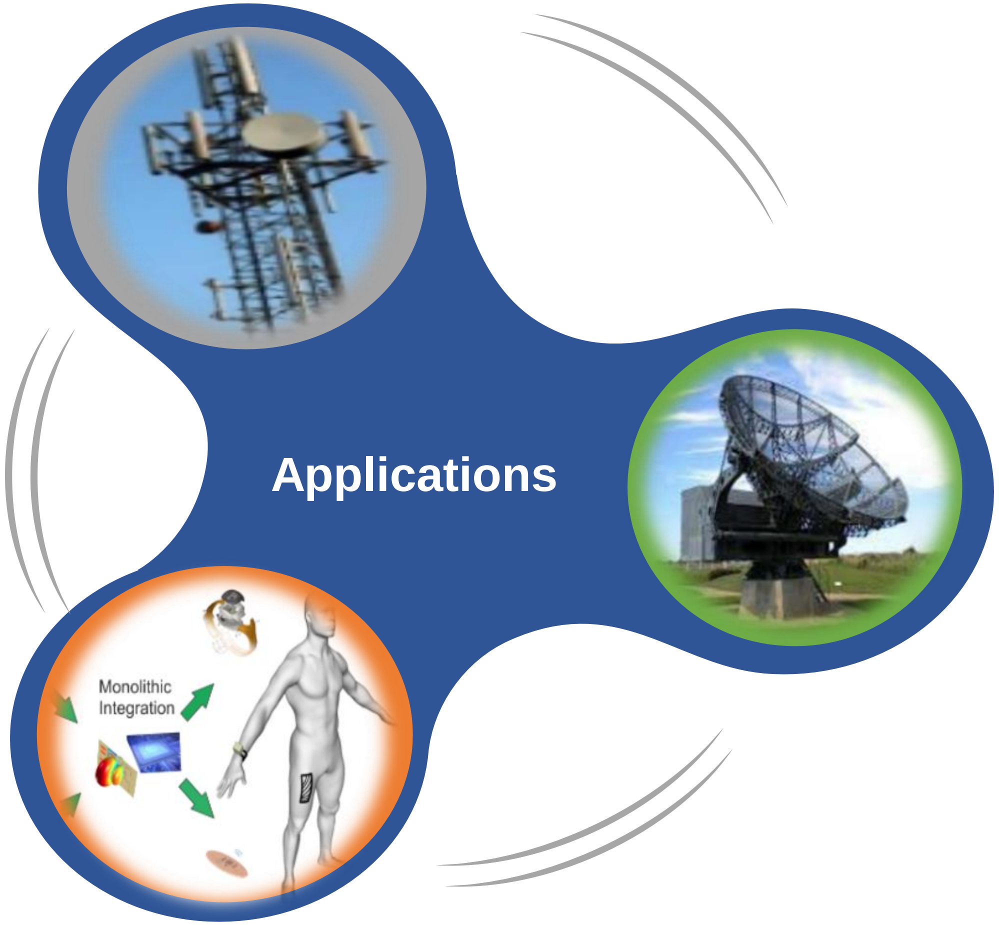
Communication

- Terrestrial
- Satellite
- Wireless Charging



Industrial and biomedical

- Biomedical Imaging
- Sensors
- Waste Treatment
- Dying
- Monitoring`



Radar

- Military Application
- Air traffic control
- Surveillance & Navigation
- Remote Sensing
- Law Enforcement

Microwave Photonics: Introduction

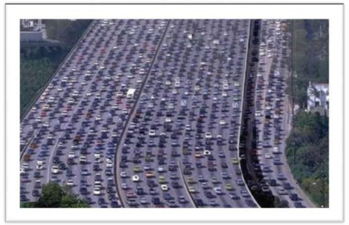
Airport and port security

Disaster prevention

Building failures

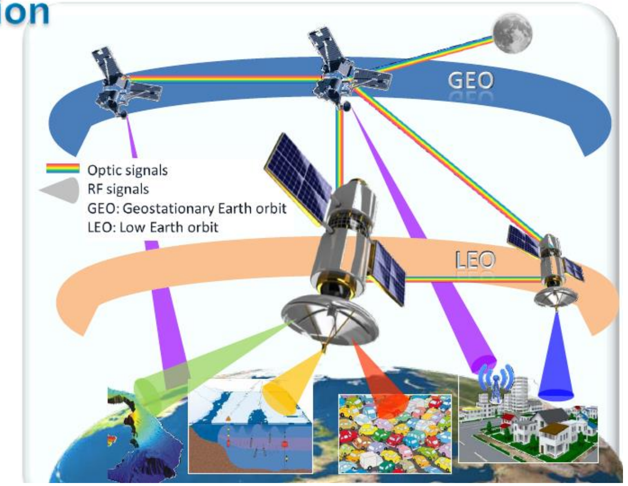
Urban traffic control

extra-urban traffic control



Military safety

Satellite: Earth observation & communication



Microwave Photonics: Introduction

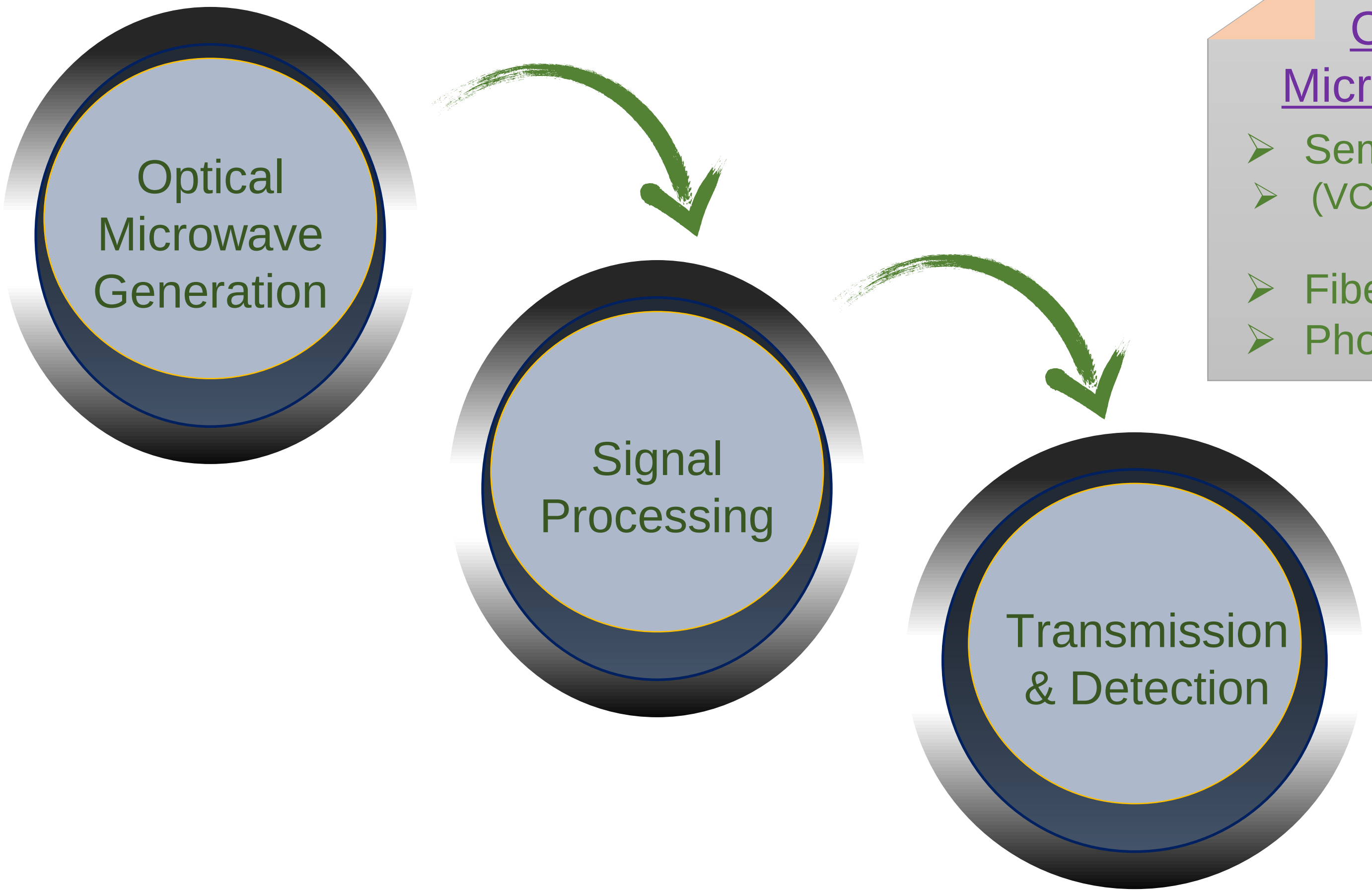


Fig. Basic Block of Microwave Photonics

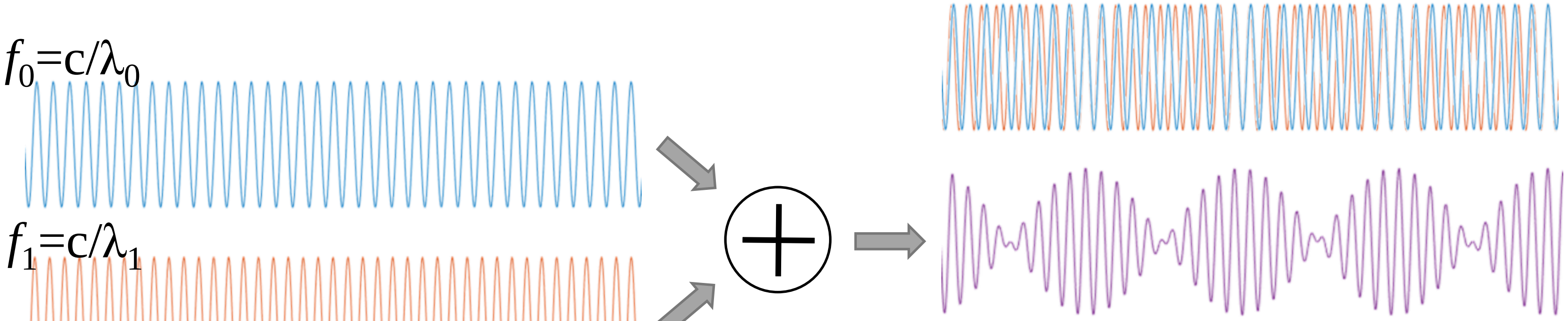
Components for Microwave Generation

- Semiconductor lasers
- (VCSELs, FP-LDs, Quantum dot lasers)
- Fiber ring Lasers
- Photonics crystal

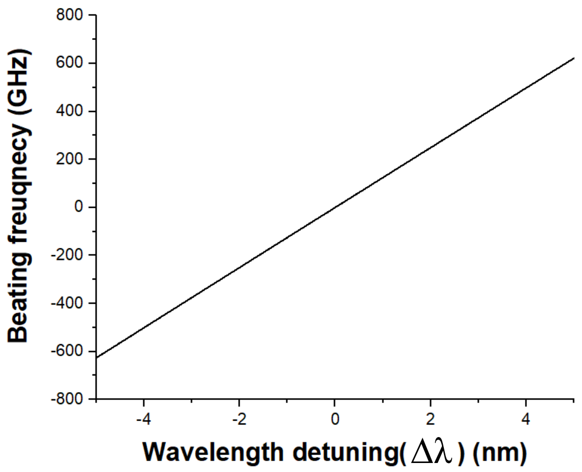
Methods for Microwave Generation

- Optical heterodyne
- Optical phase locked loops
- Dual-mode lasing emission
- Injection locking (external beam injection, feedback injection, side band injection)
- Frequency combs

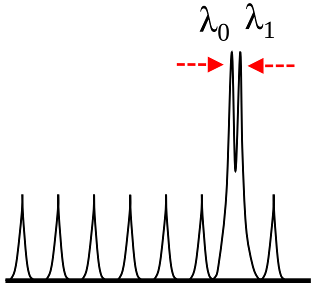
Microwave Photonics: Introduction



$$f = \frac{c}{\lambda_0} - \frac{c}{\lambda_1} \cong \frac{c(\lambda_1 - \lambda_0)}{{\lambda_0}^2} = \frac{\Delta\lambda}{{\lambda_0}^2}$$



- Microwave signal generation
  (Negative wavelength detuning injection locking)



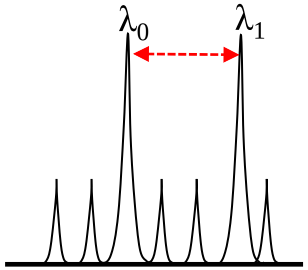
λ_0 = 1550nm

λ_1 = 1550.1nm

Beating frequency

$$f = \frac{c}{\lambda_0} - \frac{c}{\lambda_1} \cong \frac{c(\lambda_1 - \lambda_0)}{{\lambda_0}^2} = 12.48\ GHz$$

- Millimeter wave generation
  (positive wavelength detuning injection locking)



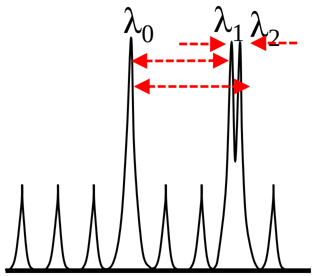
λ_0 = 1547nm

λ_1 = 1550nm

Beating frequency

$$f = \frac{c}{\lambda_0} - \frac{c}{\lambda_1} \cong \frac{c(\lambda_1 - \lambda_0)}{{\lambda_0}^2} = 375.3\ GHz$$

- Microwave & millimeter wave generation
  (Negative wavelength detuning injection locking)



λ_0 = 1547nm

λ_1 = 1550nm

λ_2 = 1550.1nm

$$f_1 = \frac{c}{\lambda_0} - \frac{c}{\lambda_1} \cong \frac{c(\lambda_1 - \lambda_0)}{{\lambda_0}^2} = 375.3\ GHz$$

$$f_2 = \frac{c}{\lambda_0} - \frac{c}{\lambda_1} \cong \frac{c(\lambda_2 - \lambda_0)}{{\lambda_0}^2} = 387.78\ GHz$$

$$f_3 = \frac{c}{\lambda_0} - \frac{c}{\lambda_1} \cong \frac{c(\lambda_1 - \lambda_2)}{{\lambda_0}^2} = 12.48\ GHz$$

Microwave Photonics: Operating Principle, NIL

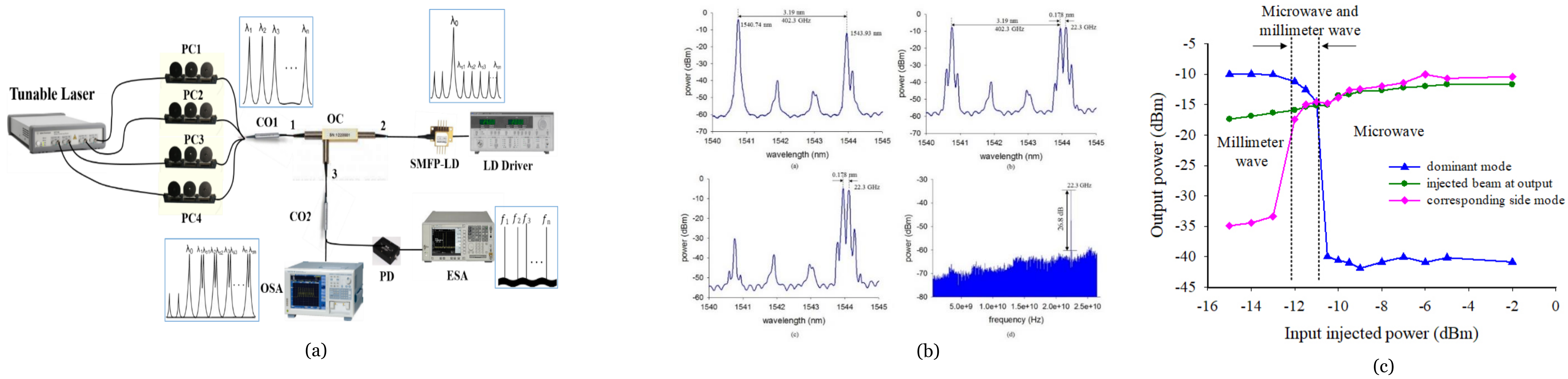


Fig. Demonstration of RF generation NIL (a) basic block (b) spectrum output (c) Generation of Millimeter wave and Microwave

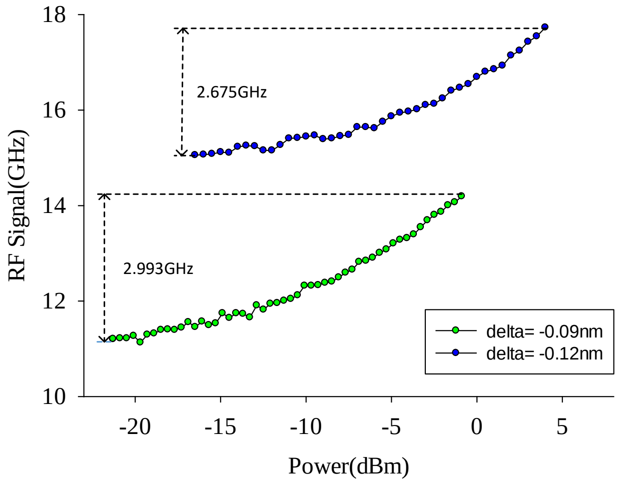
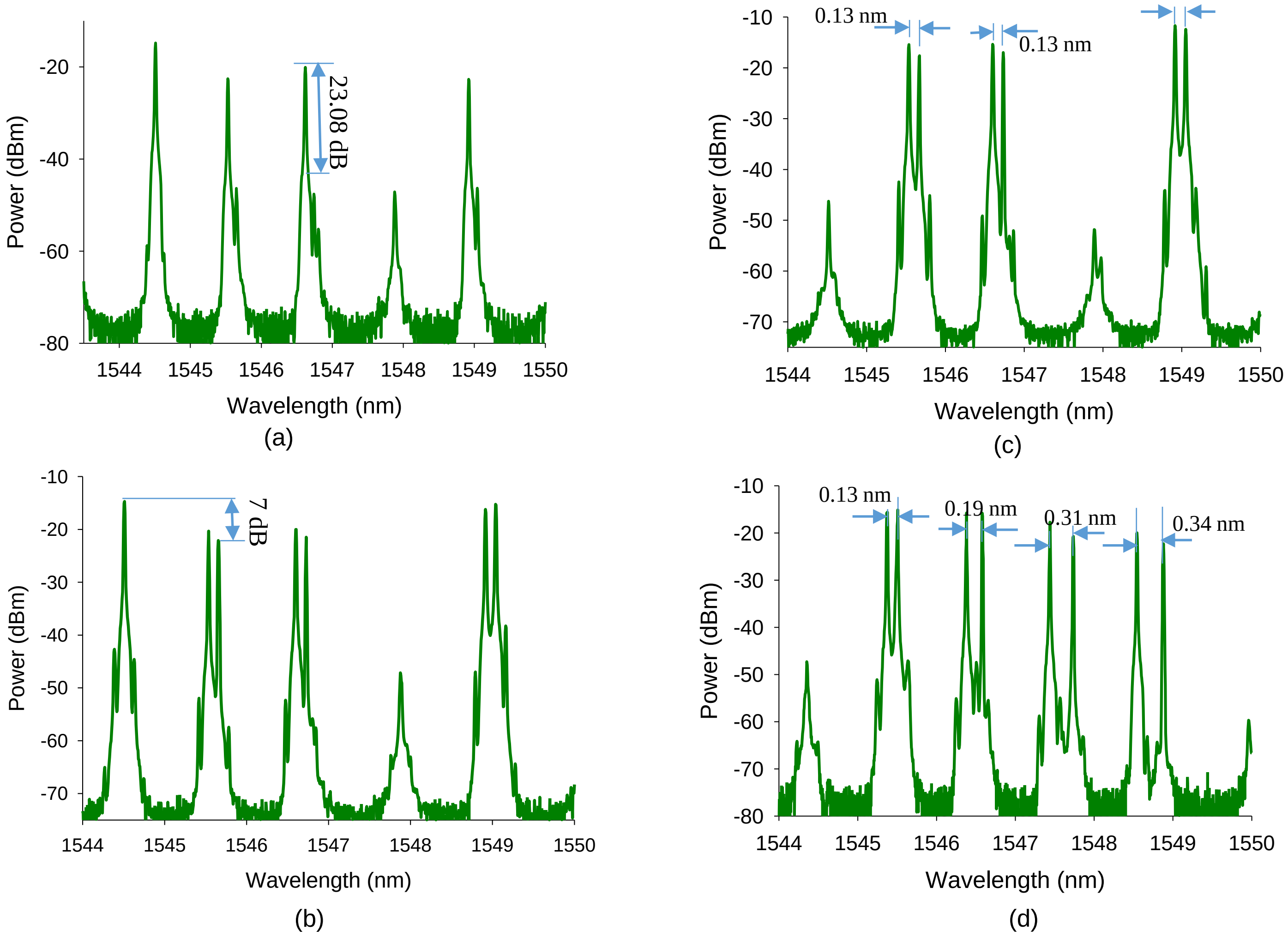


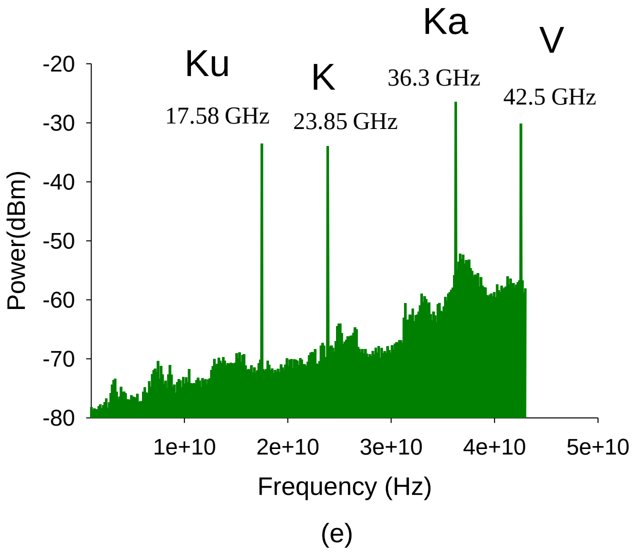
Fig. Redshift in SMFP-LD

RF Signal / Optical Injection	Millimeter-wave signal only	Micro/Millimeter wave signals	Microwave Signal only
Positive optical injection	√ (Weak injection)	× (dominant mode suppressed)	√ (dominant mode suppressed)
Negative optical injection	√ (Weak injection)	√ (Moderate injection)	√ (Strong injection)

Ref: H. Chen, B. Nakarmi, M. Rakib Uddin, and S. L. Pan. *IEEE Photonics Journal*,2019, Zhang Limin and et. Al, Photonics Asia,2019

Microwave Photonics: Multiband RADAR Signal Generation





SNR is about 30 dB

Generation of Multi-band Radar Signal (a) millimeter only (b) millimeter and microwave (c and d)microwave wave with 3 and 4 beam injection (e) electric RF Mutli-band RADAR signal

Ref: B. Nakarmi, and et. Al., TMTT 2018

Microwave Photonics: RF Switching and Generation

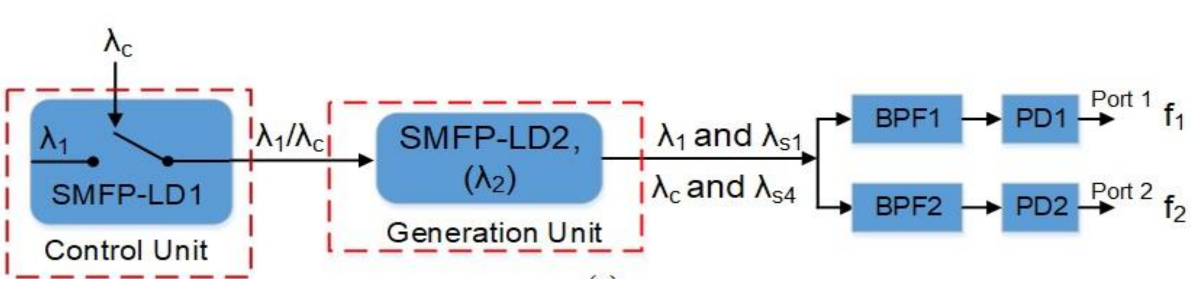


Fig. Block diagram of switching of the RF generation

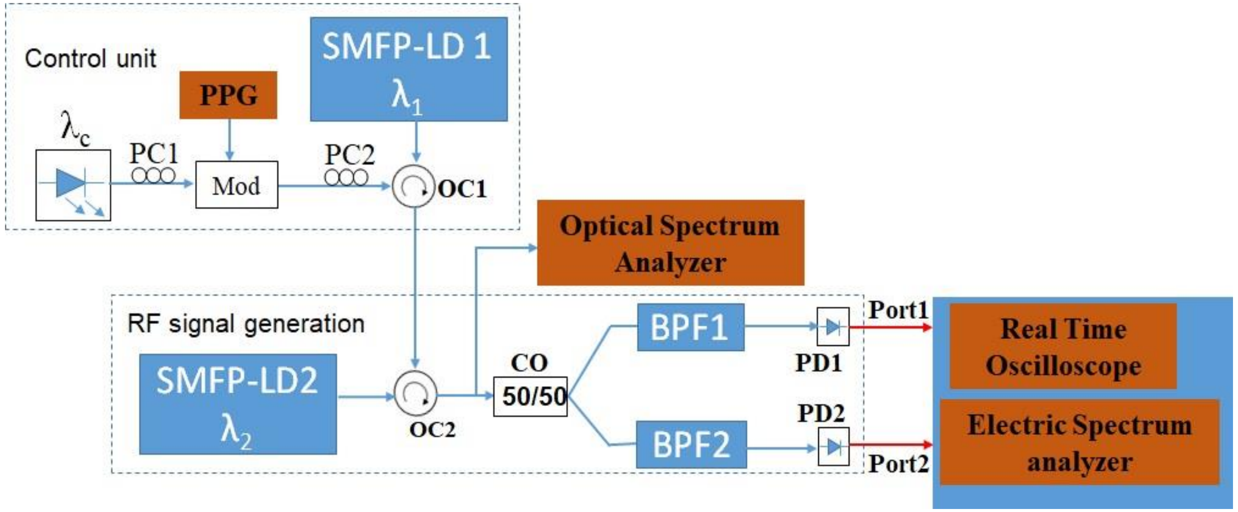


Fig. Experimental setup of the proposed scheme of switching of RF signal generation

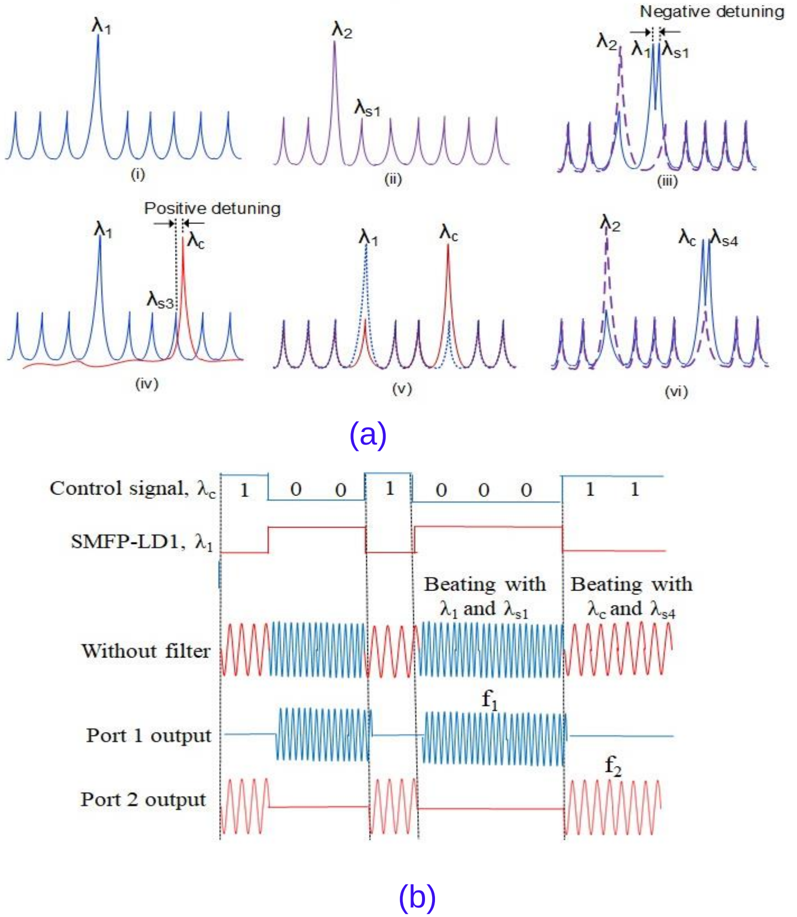
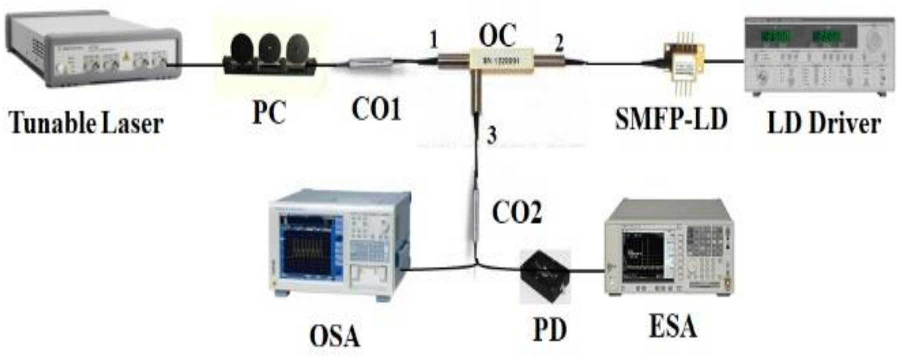


Fig. Switching of the RF generation (a) schematic illustration of operating principle through schematic of spectrum diagram (b) schematic illustration of switching of the RF generation

Ref: B. Nakarmi, H. Chen, Y. H. Won, and S. L. Pan. *IEEE/OSA JLT*, 2018

Microwave Photonics: Generation and hopping results



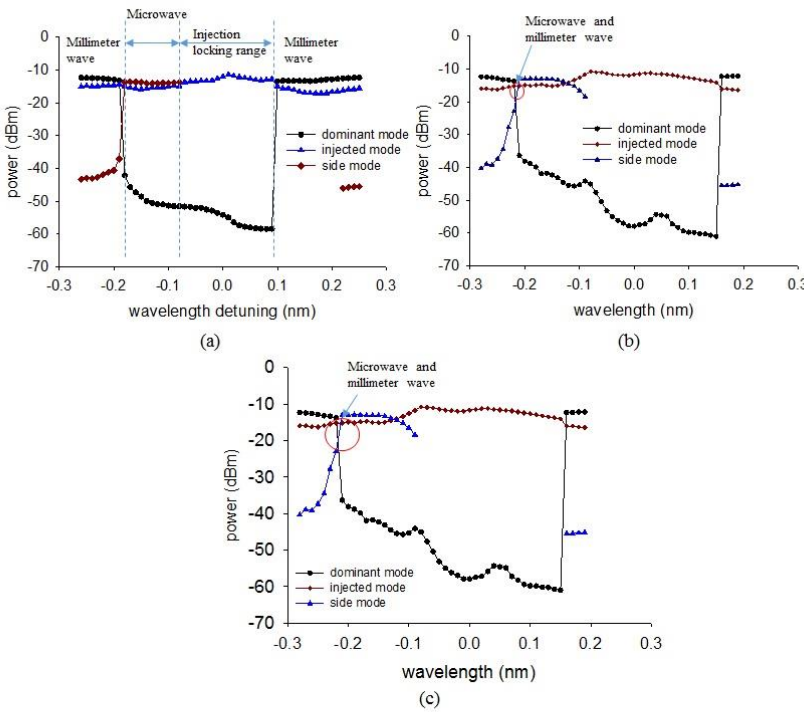
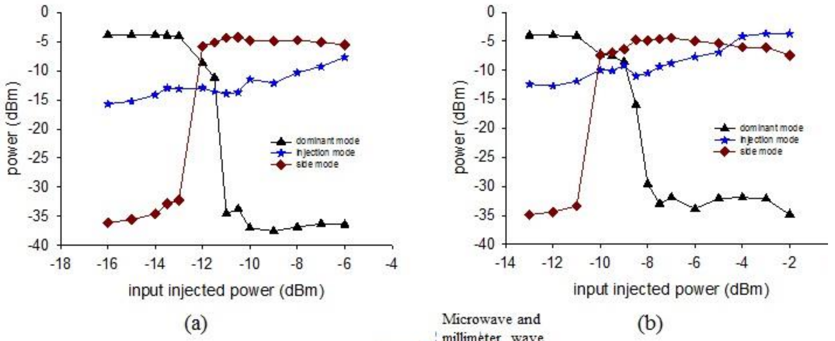


Fig. Effect of mode of injection with constant power (a) 1st mode, (b) 3rd mode and (c) 5th mode



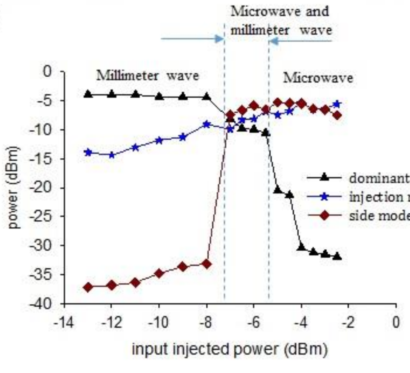


Fig. Output power analysis with different wavelength detuning (a) 0.08 nm, (b) 0.12 nm and (c) 0.17 nm

Ref: B. Nakarmi, H. Chen, Y. H. Won, and S. L. Pan. IEEE *TMTT*, 2018

Microwave Photonics: RF Switching results

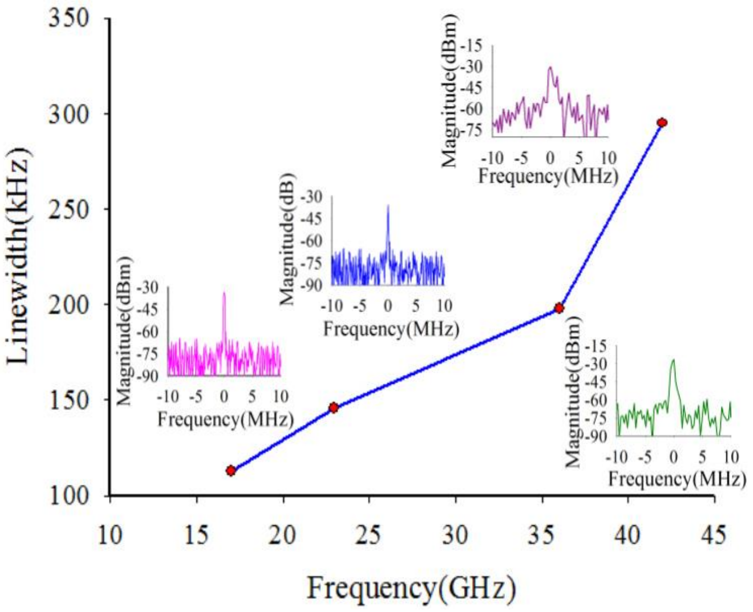


Fig. Linewidth Measurement

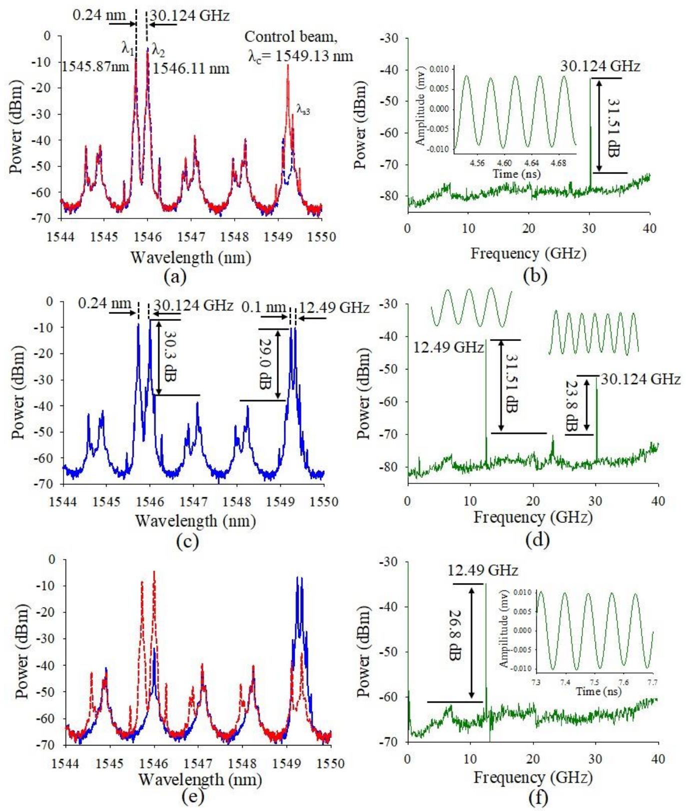


Fig (a) Output from SMFP-LD2 when the control is absent (b) ESA and RTO diagram of RF signal of (a), (c)output spectrum from SMFP-LD2 with weak injection locking of control signal on SMFP-LD1 (d) ESA and RTO diagram of RF signal of (c), and (e) output spectrum of weak injection locking with increase in power of control signal i.e., strong injection by control signal (f) ESA and RTO diagram of RF signal of (e)

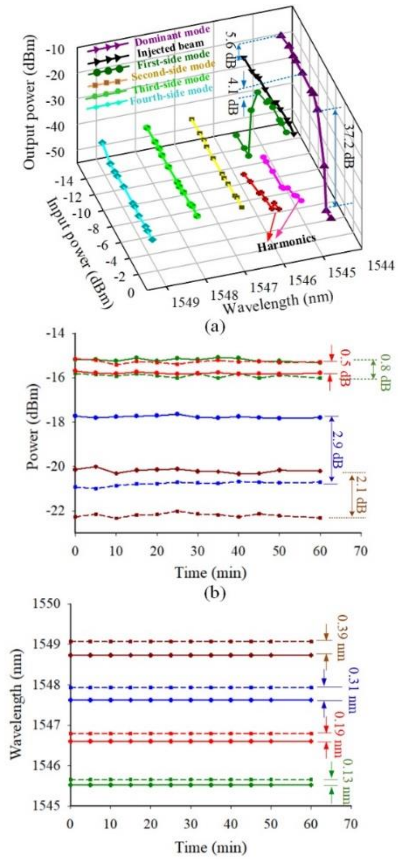


Fig. Power and wavelength stability

Ref: B. Nakarmi, H. Chen, Y. H. Won, and S. L. Pan. IEEE *TMTT*, 2018

Microwave Photonics: Switching results

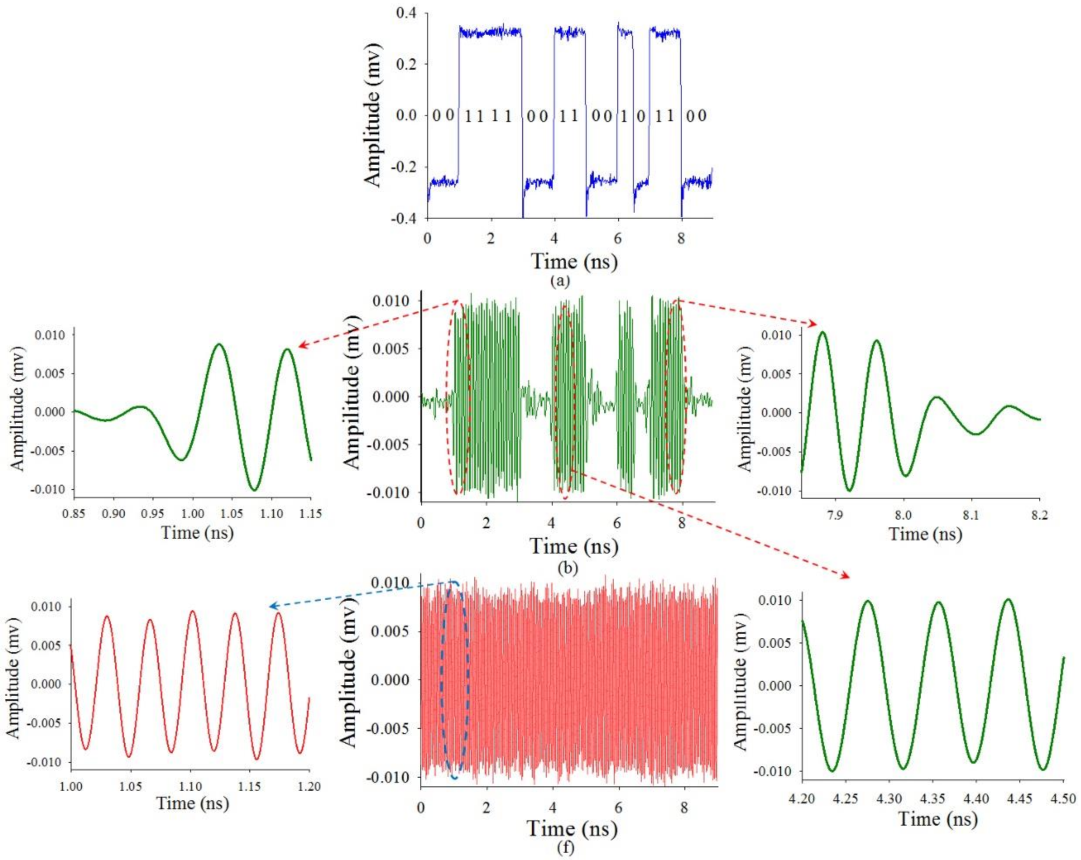


Fig. Oscilloscope traces of weakly injection case (a) 2-Gbps, 16-bit NRZ control signal (b) output from port 1 (b) output from port 2

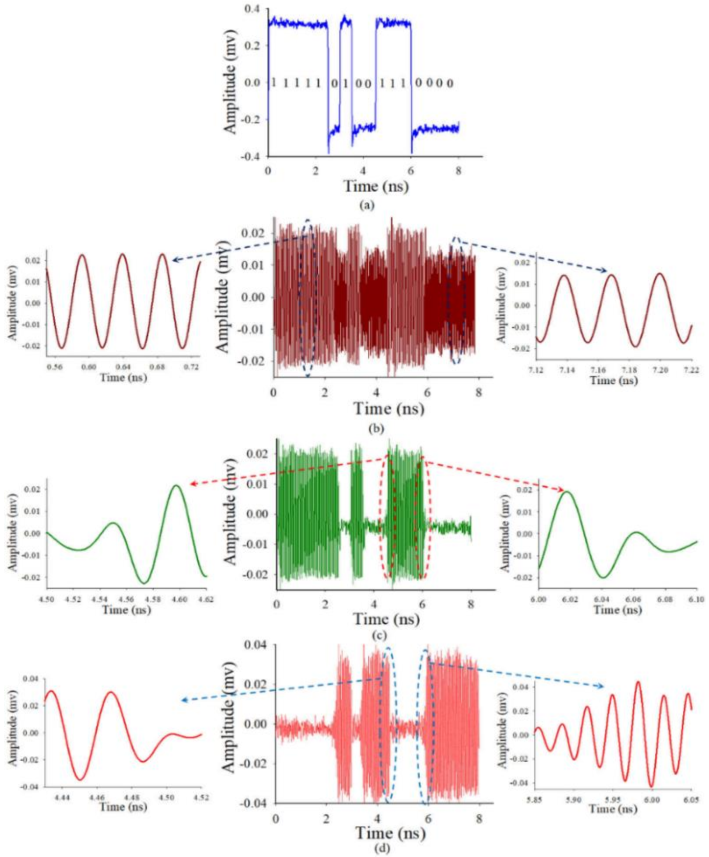


Fig. Oscilloscope traces for (a) 16-bit, 2-Gbps NRZ control signal (b) Switching of RF generation between (c) output from port 1 and (d) output from port 2

Ref: B. Nakarmi, H. Chen, Y. H. Won, and S. L. Pan. IEEE *TMTT*, 2018
Ref: B. Nakarmi, H. Chen, Y. H. Won, and S. L. Pan. *IEEE/OSA JLT*, 2018

Microwave Photonics: OEO

- OEO (optoelectronic oscillator)works as a microwave oscillator using optical devices to store energy.

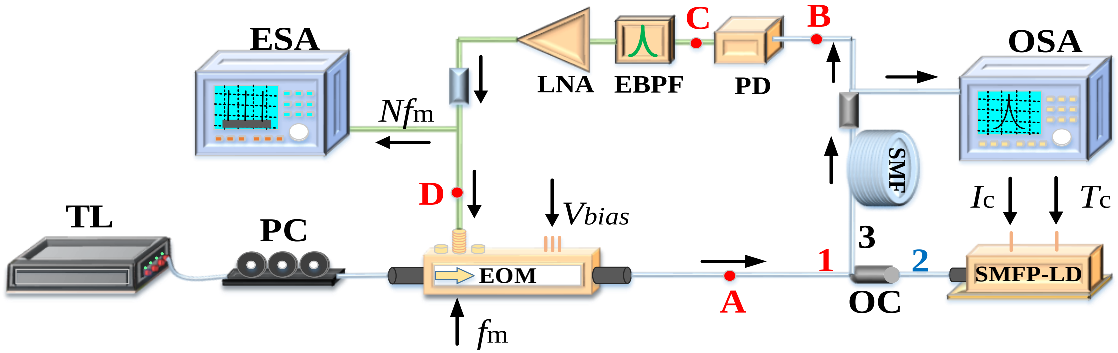


Fig. Experimental setup of the proposed harmonics locked RF multiplier with an optoelectronic

- If gain of the OEO loop is higher than the loss, a high-purity oscillating multiple RF frequency can be generated.

Closed OEO loop

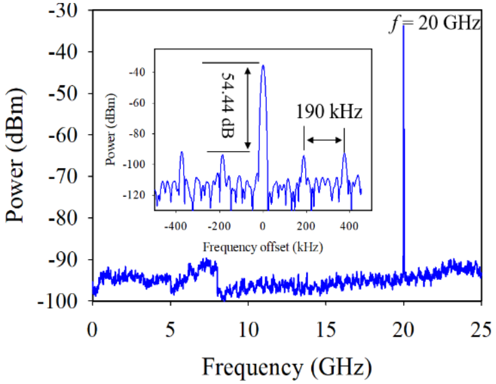


Fig. The electric spectrum of the RF signal with the sextuple frequency

Open OEO loop

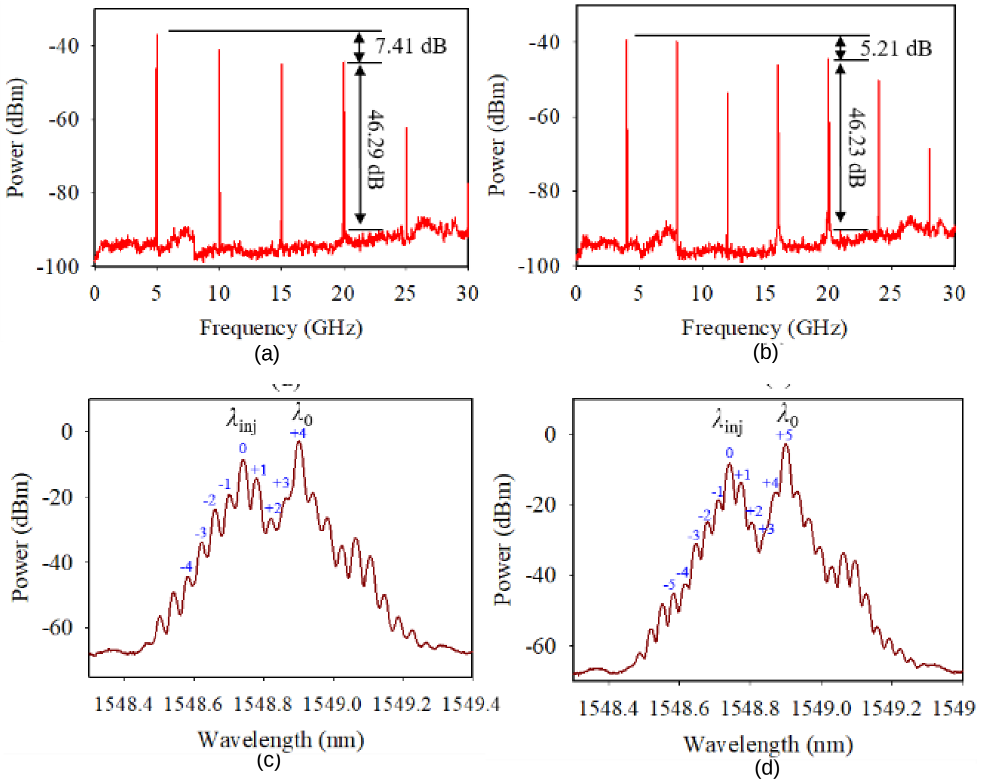
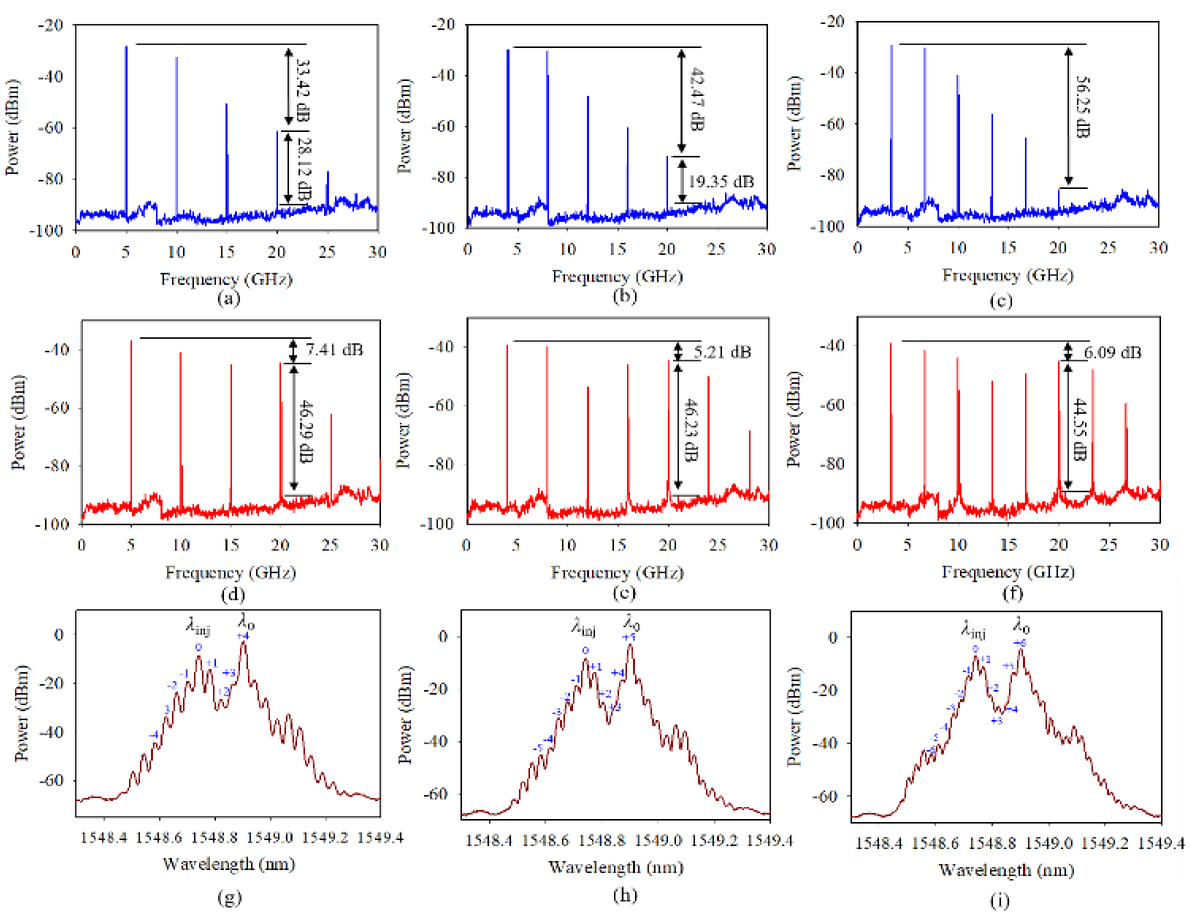


Fig. (a)(b) The electric spectrum of the output of SMFP-LD after harmonics injection locking with N = 4, 5, and 6 and the corresponding optical spectrum(c)(d)

Ref: H. Chen, B. Nakarmi, Zhang Limin, Bassi Snehi, and S. L. Pan. IEEE Access Under Review

Microwave Photonics: OEO



Without injection fm = 20/N, (a) N =4, (b) N =5, and (c) N =6

With harmonics locked with (d) N =4, (e) N =5, and (f) N =6

Corresponding Optical spectrum

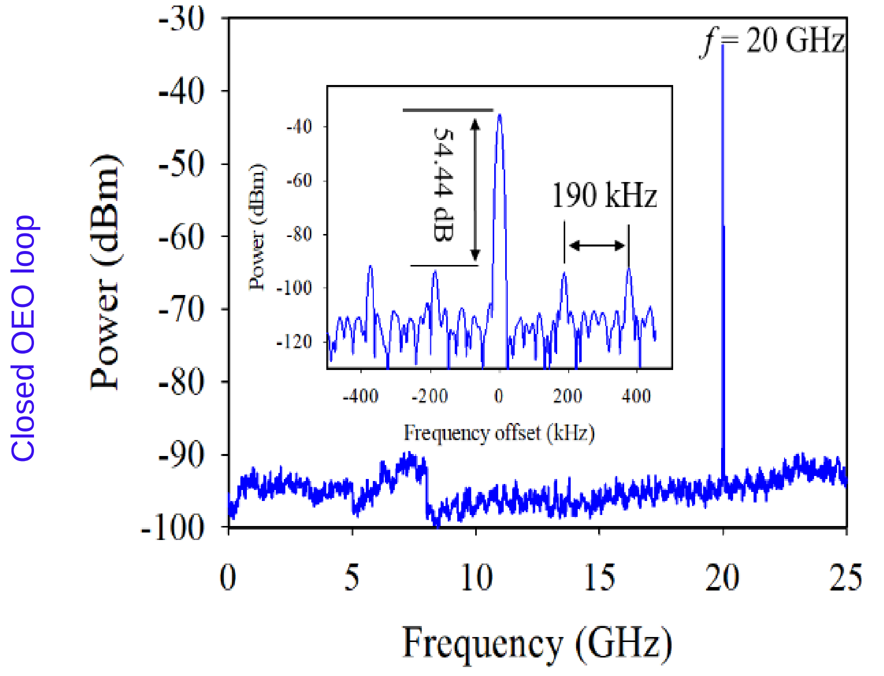
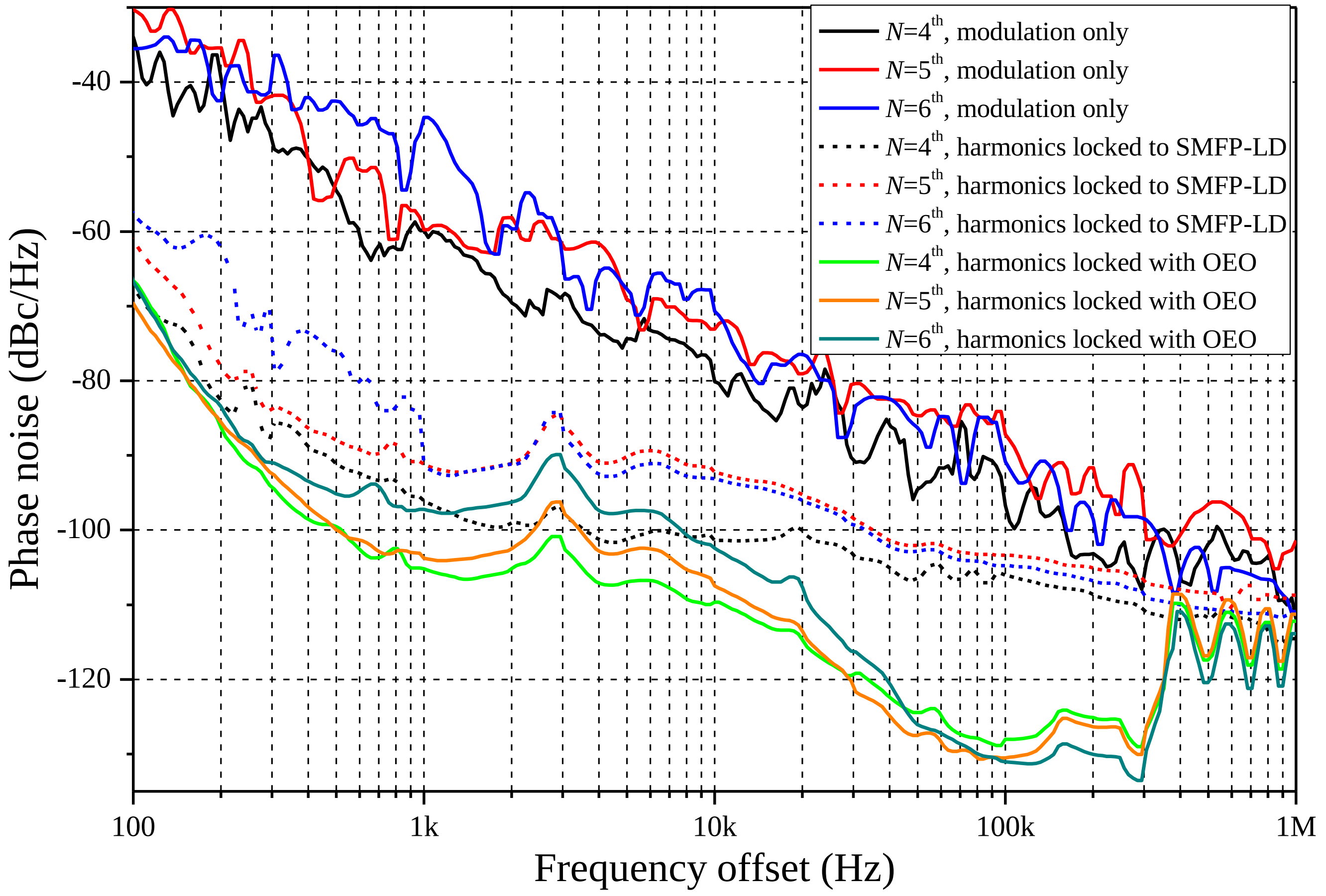


Fig. The electric spectrum of the RF signal with the sextuple frequency

- If gain of the OEO loop is higher than the loss, a high-purity oscillating multiple RF frequency can be generated.

Ref: H. Chen, B. Nakarmi, Zhang Limin, Bassi Snehi, and S. L. Pan. Under preparation for JSTQE, 2020

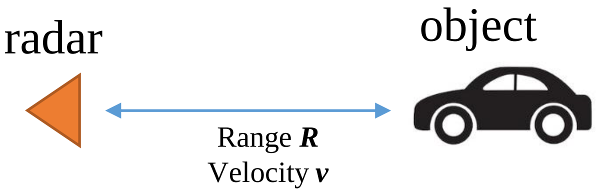
Microwave Photonics: OEO

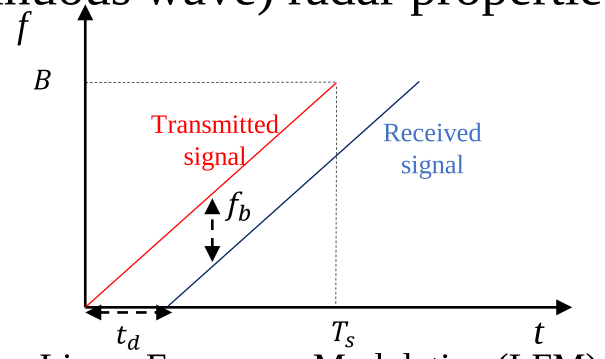


Phase noise analysis

Microwave Photonics: FMCW

Basic FMCW (frequency modulated continuous wave) radar properties

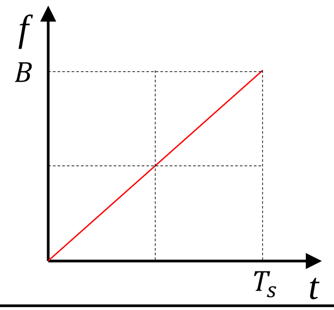
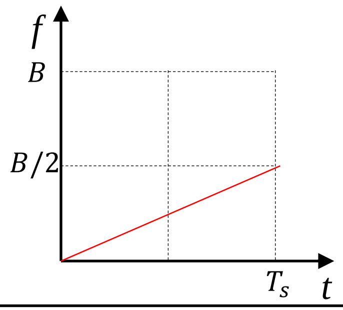
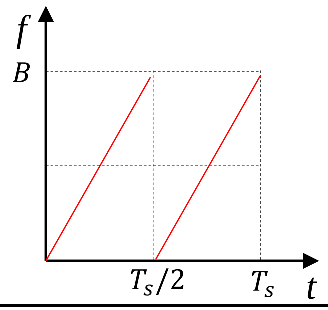
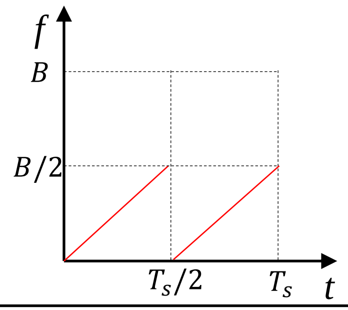




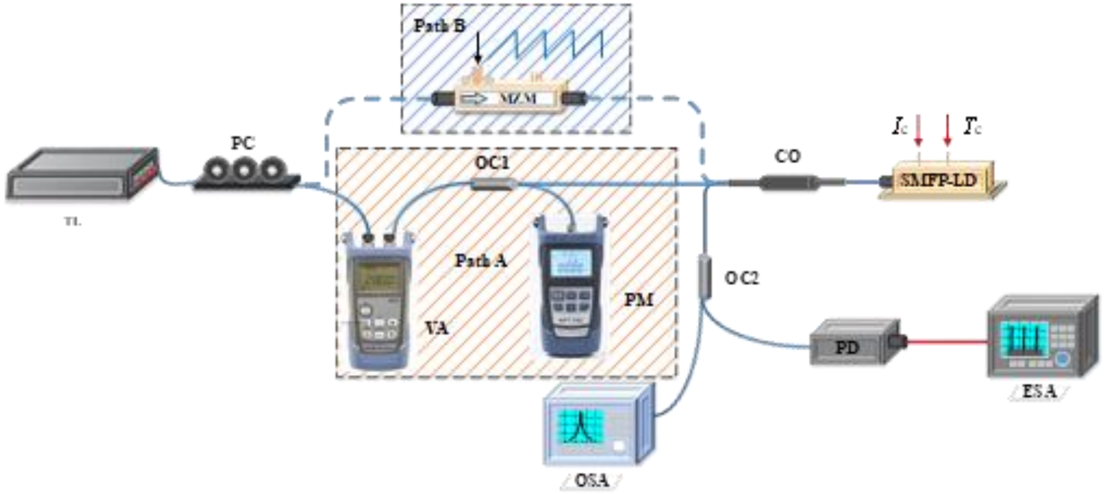
Linear Frequency Modulation (LFM)

$$R=\frac{ct_d}{2}=\frac{cf_bT_s}{2B}\qquad \Delta R_{res}=\frac{c}{2B}\qquad R_{max}=\frac{cT_s}{10}$$

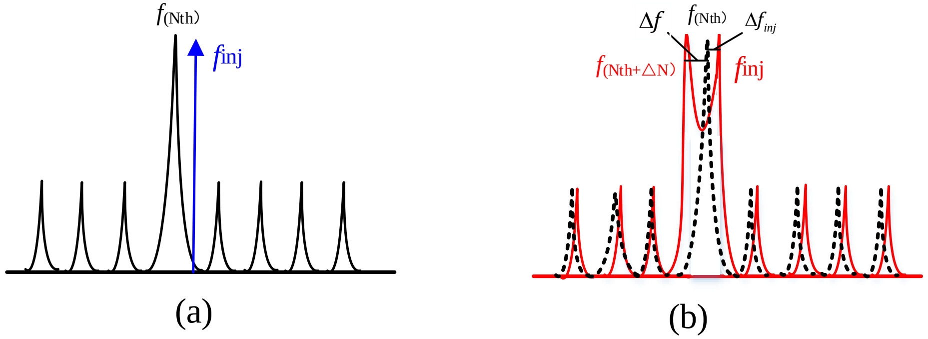
$$v=\frac{\lambda\Delta\phi}{4\pi T_s}\qquad \Delta v_{res}=\frac{\lambda}{2NT_s}\qquad v_{max}=\frac{\lambda}{4T_s}$$

Waveform	Waveform A	Waveform B	Waveform C	Waveform D
				
Bandwidth	B (3GHz)	**B/2 (1.5GHz)**	B (3GHz)	**B (1.5GHz)**
Sweep Time	T_s (1ms)	T_s (1ms)	**T_s/2 (0.5ms)**	**T_s/2 (0.5ms)**
Range resolution	c/2B (5cm)	c/4B (10cm)	c/2B (5cm)	c/4B (10cm)
Maximum range	cT_s/10 (30km)	cT_s/10 (30km)	cT_s/20 (15km)	cT_s/20 (15km)
Maximum velocity	$\lambda/4T_s$ (7.7km/h)	$\lambda/4T_s$ (7.7km/h)	$\lambda/2T_s$ (15.4km/h)	$\lambda/2T_s$ (15.4km/h)

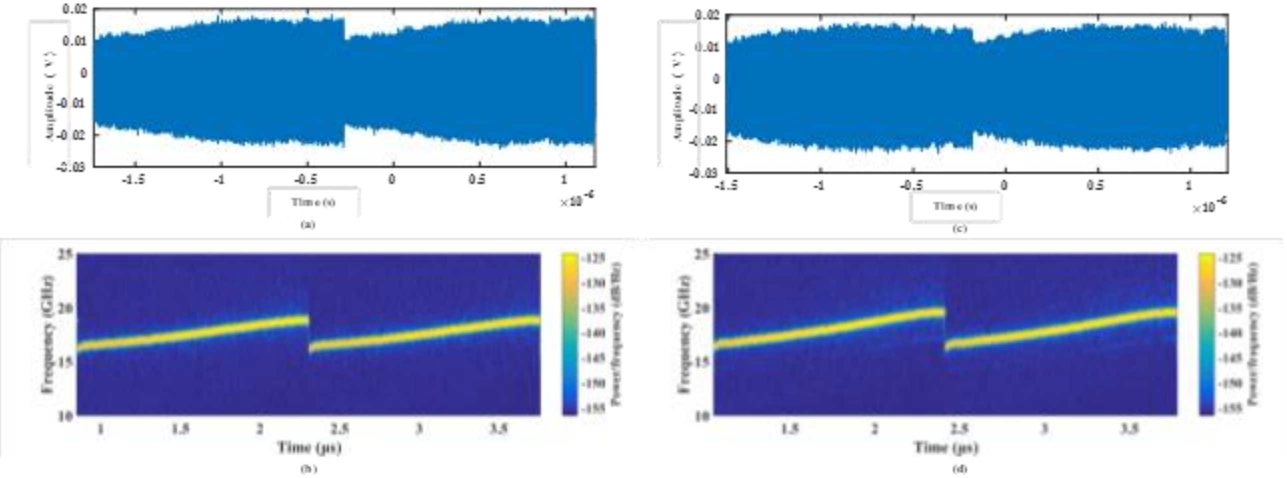
Microwave Photonics: Redshift and LFM Generation



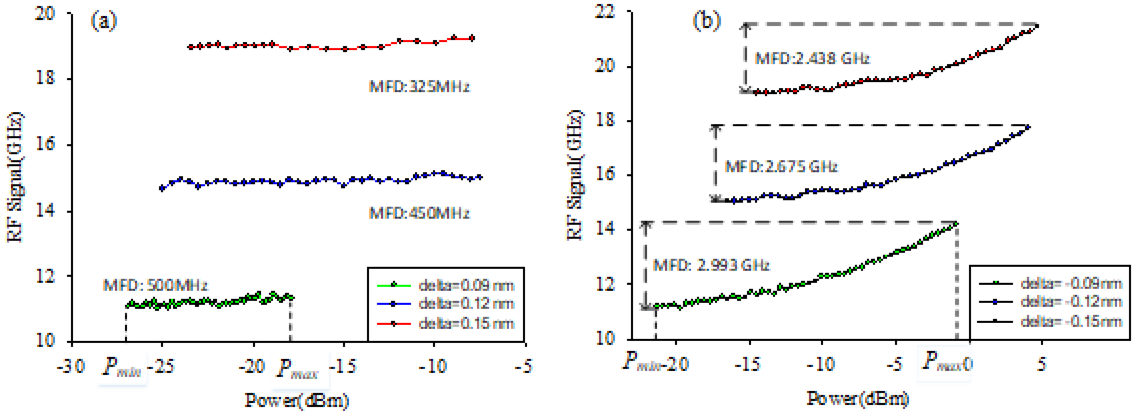
(a) Experiment set up for Redshift Analysis and LFM Generation



(a) SMFP-LD without optical injection, (b) Redshift in SMFP-LD with optical injection.



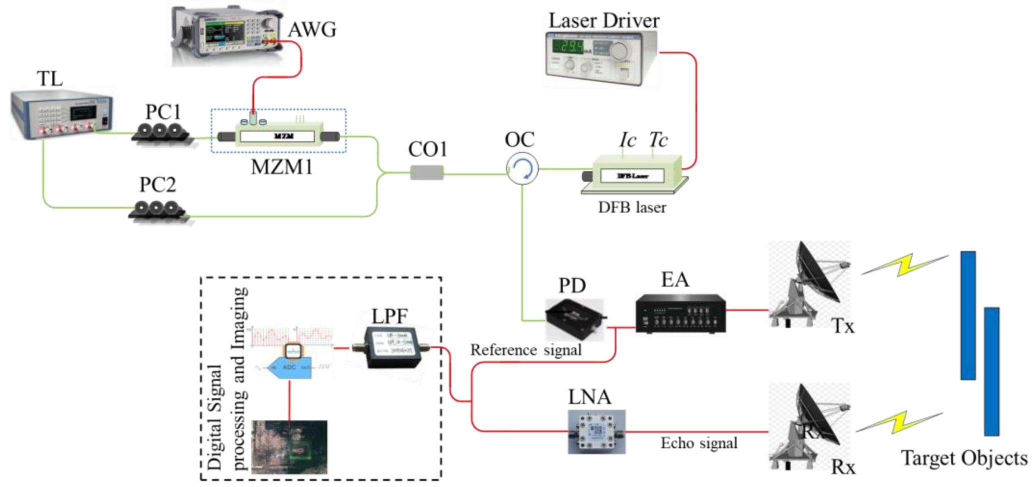
Measured waveform and time frequency diagram for dominant mode and 1st mode



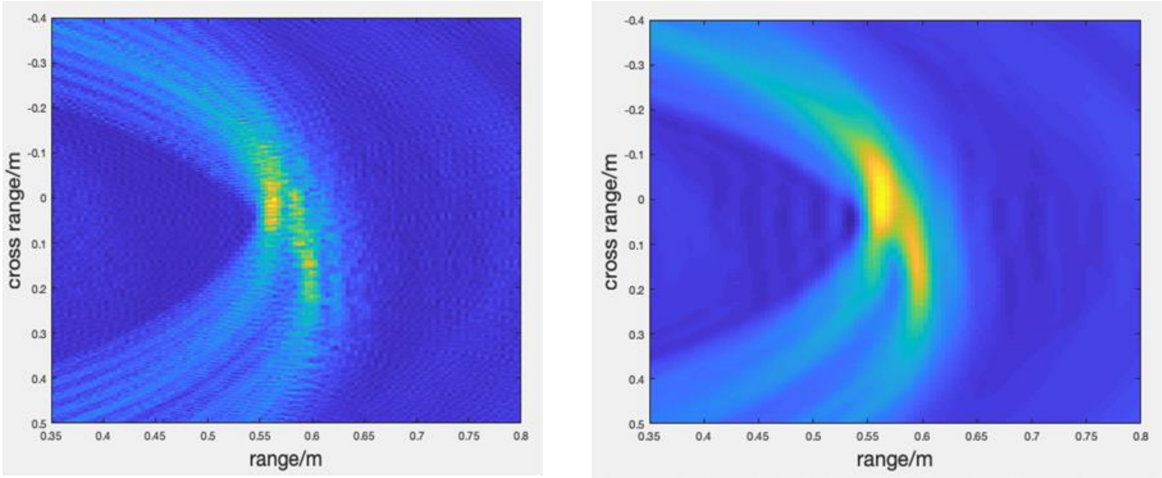
Redshift and BW obtained in SMFP-LD with different wavelength detuning (a) PIL (b) NIL

Ref: Zhang Limin and et. al, Photonics Asia 2019 & SPIE optical Engineering

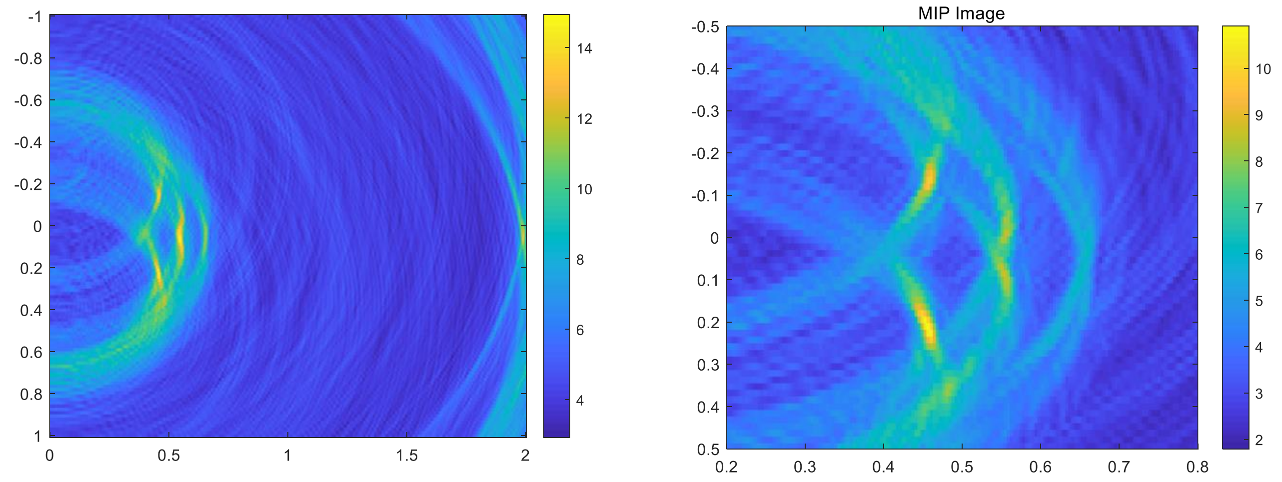
Microwave Photonics: LFM Generation and Imaging

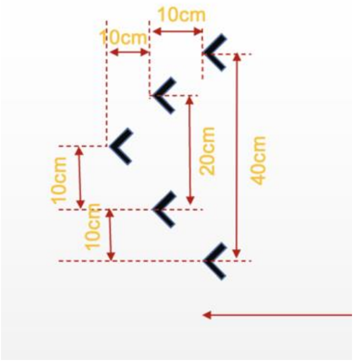


(a) Experiment set up for target object detection and Imaging



(b) Imaging of two objects





(c) Imaging of five objects with identical distances

Ref: B. Nakarmi, U. Nakarmi, Ikechi, S.L. Pan , Invited talk, IEICE,
B. Nakarmi et. Al , Under preparation

Microwave Photonics: Secure Communication

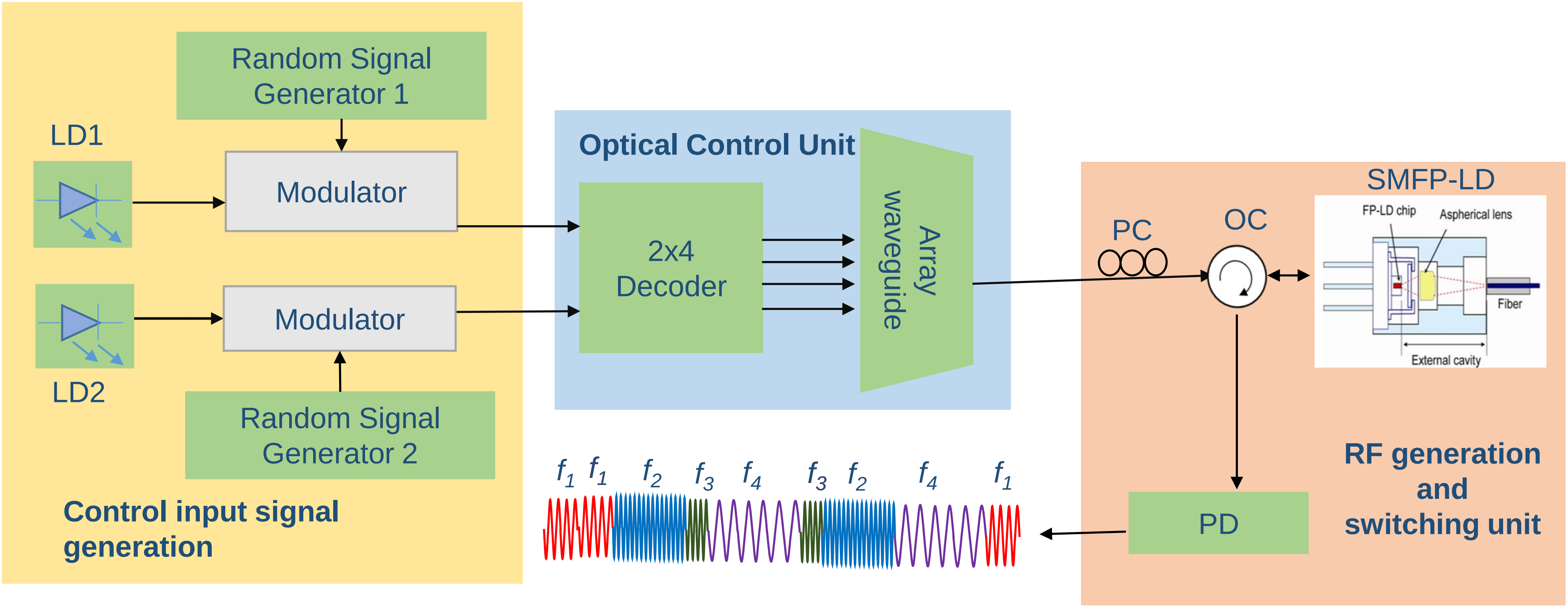


Fig. Proposed scheme for Secure communication with RF

Ref: B. Nakarmi, H. Chen, Y. H. Won, and S. L. Pan. Preparation

Microwave Photonics: Cognitive RADAR

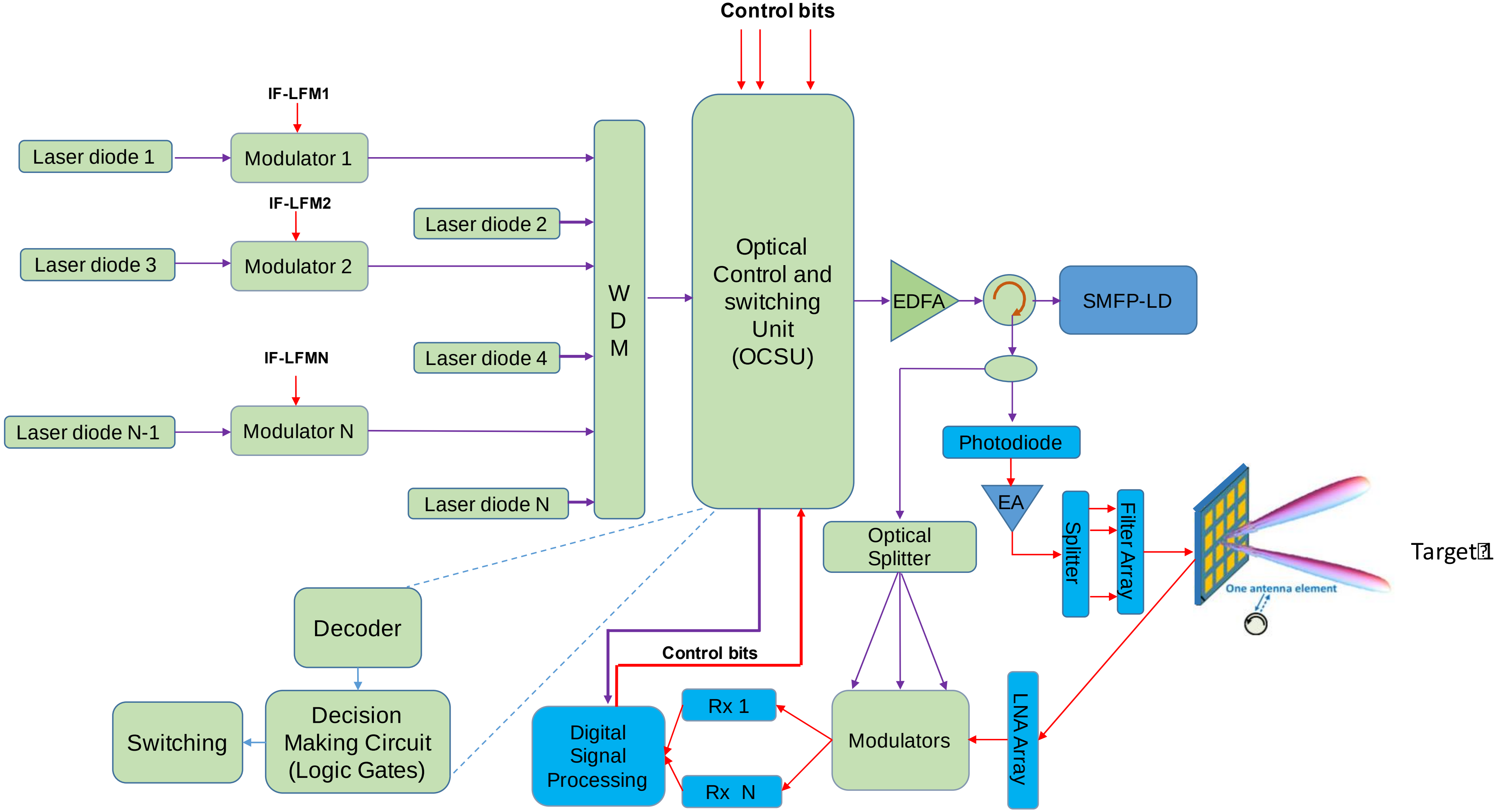


Fig. Towards Cognitive Radar

Ref: B. Nakarmi, H. Chen, Y. H. Won, and S. L. Pan. *Preparation for submission*

Microwave Photonics: Interference Mitigation

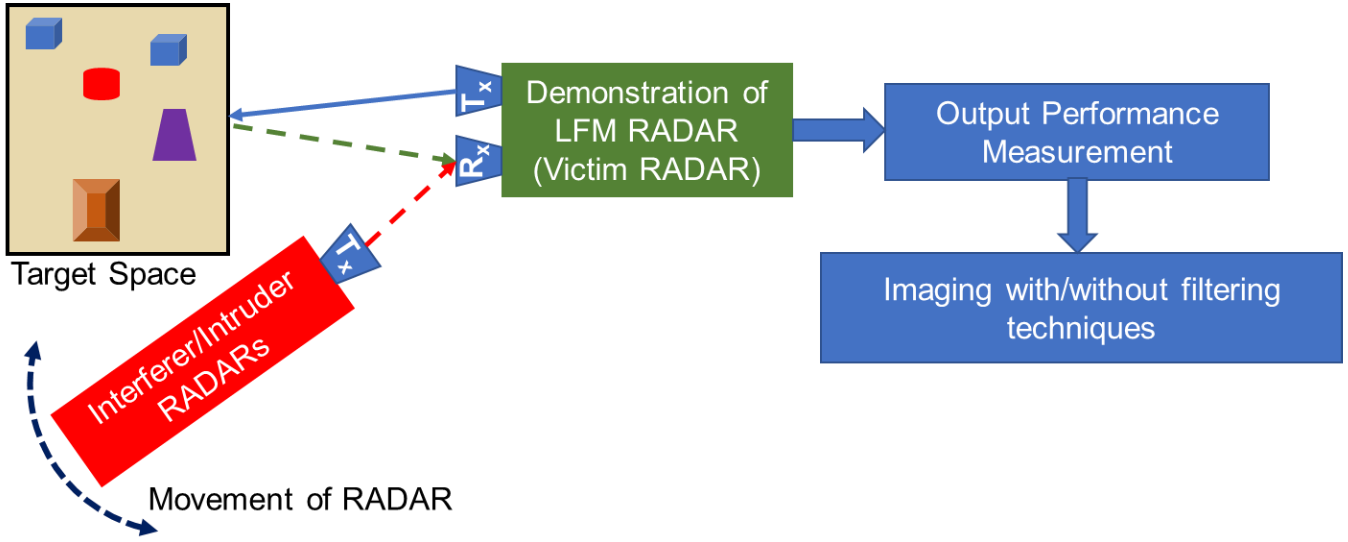


Fig. Multi-Radar Environment

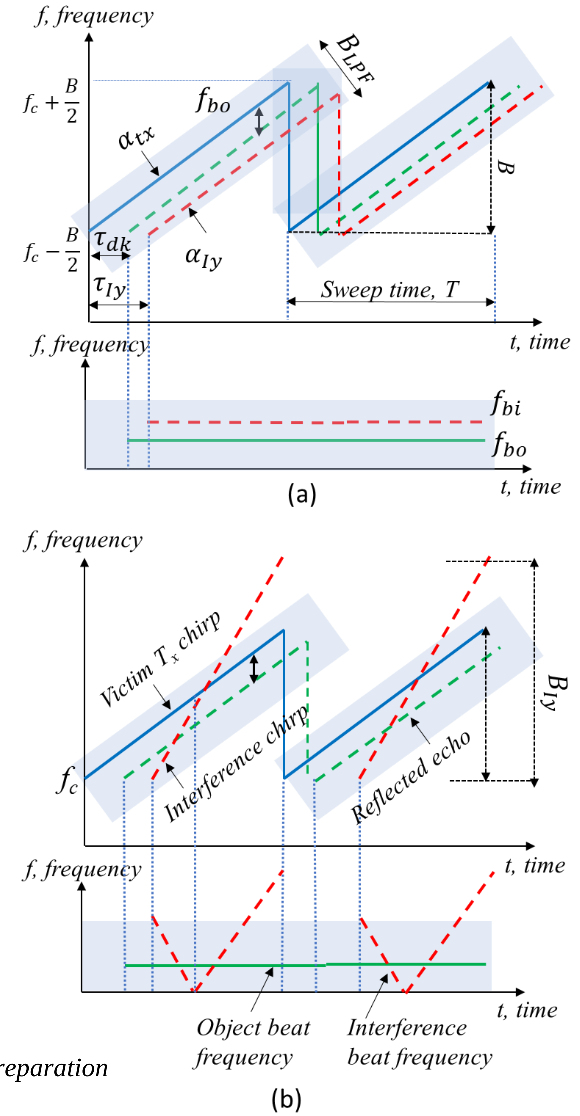


Fig. Beat frequencies

Ref: B. Nakarmi, Bai yan Song, chuanqi, U. Nakarmi. Wang Xiangchun, Ikechi augustine, and S. L. Pan., *Under preparation*

Microwave Photonics: Interference Mitigation

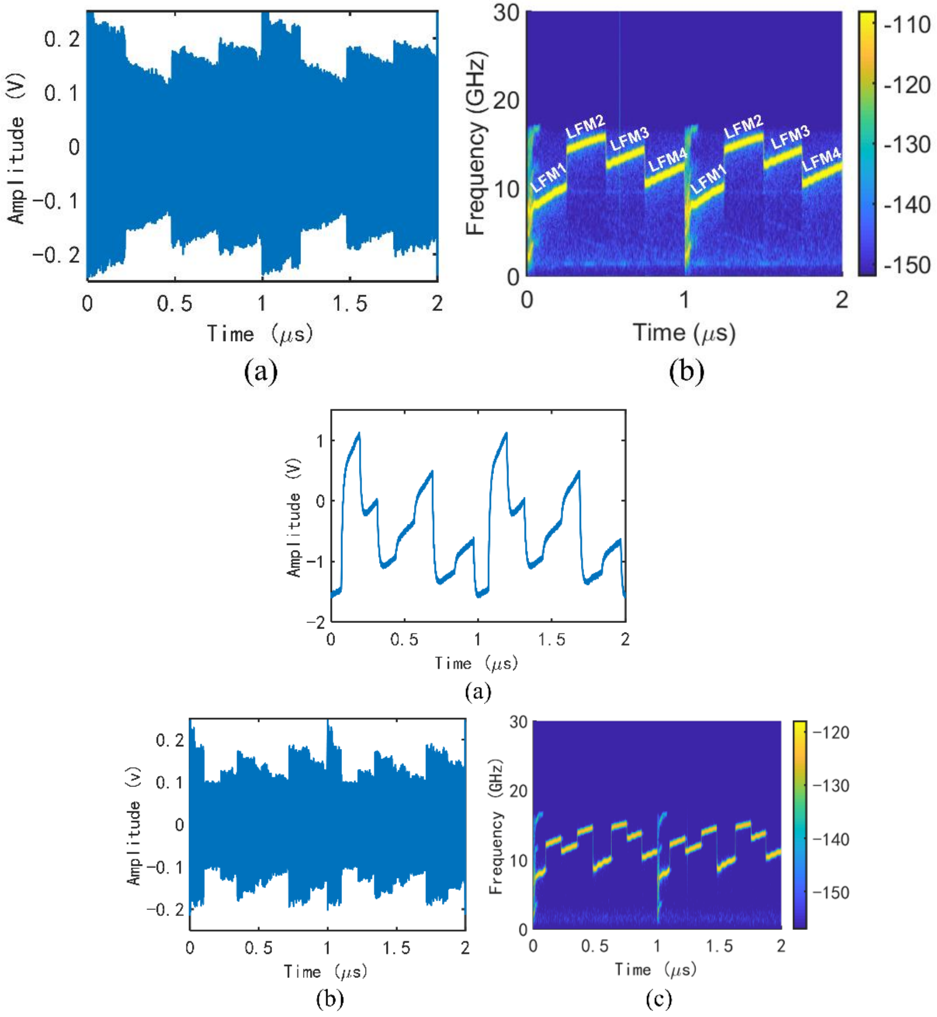


Fig. RHLFM generation with four and eight hoping

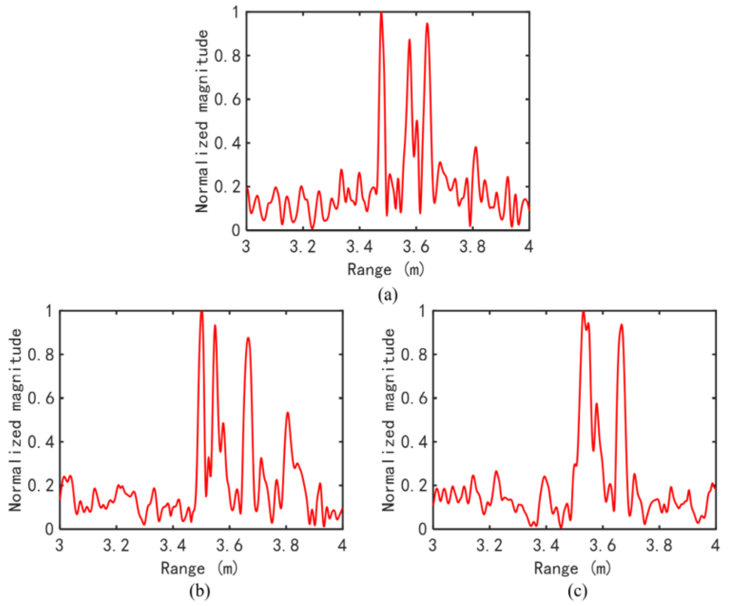


Fig. Detection With LFM in interference Scenario

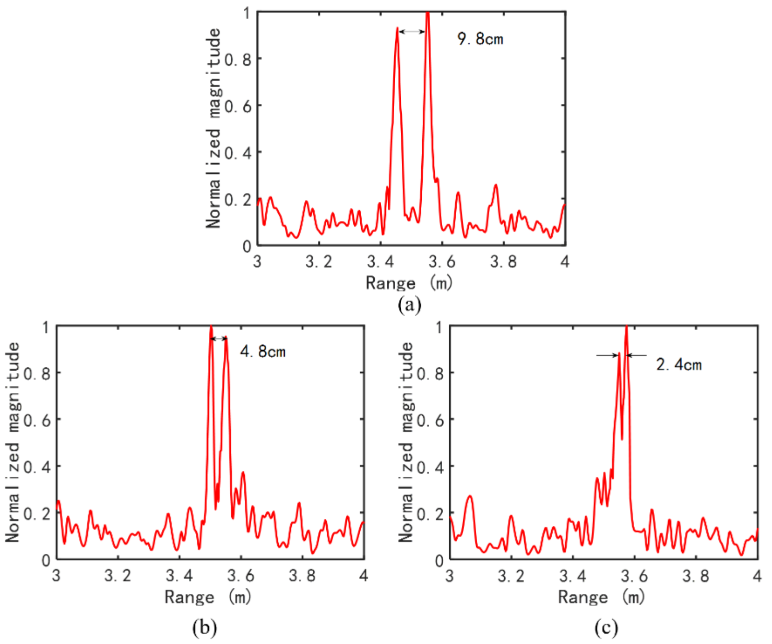


Fig. Detection With RHLFM in interference Scenario

Ref: B. Nakarmi, Bai yan Song, chuanqi, U. Nakarmi. Wang Xiangchun, Ikechi augustine, and S. L. Pan., *JLT*, *2022*

THANKS

2023

Appendices

01

Digital Photonics

◎Logic Units

◎Combinational Circuits

◎WDM enabled Memory

Digital Photonics: Logic units

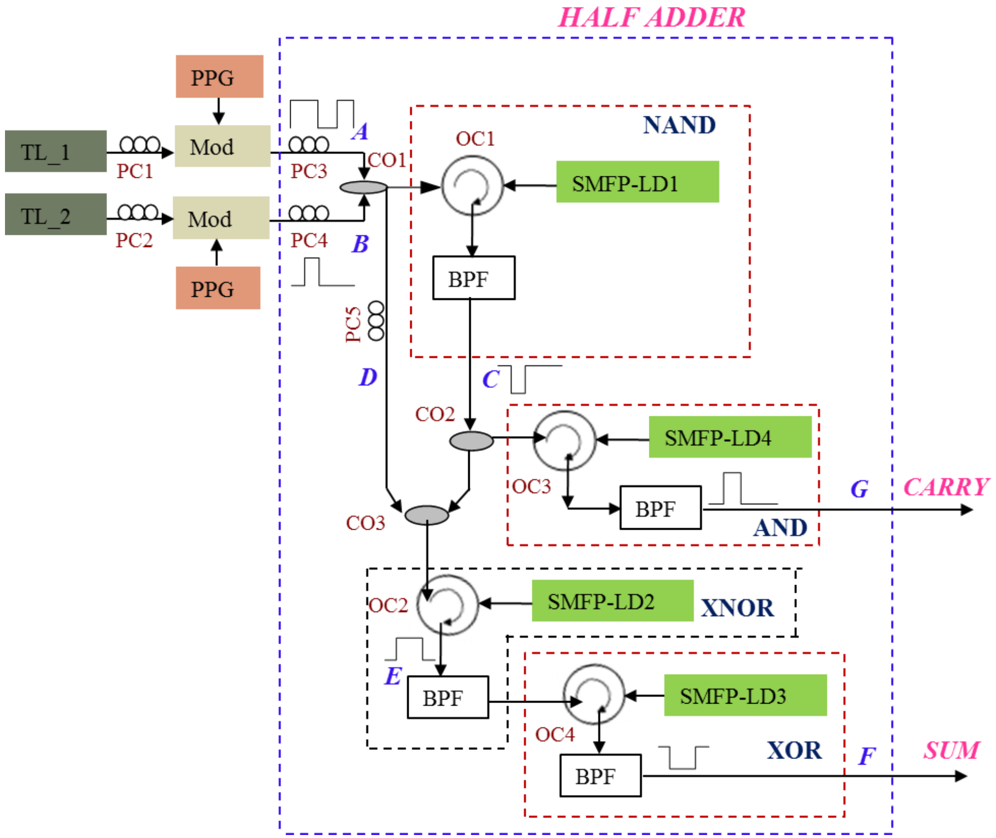


Fig. Experimental setup for half adder

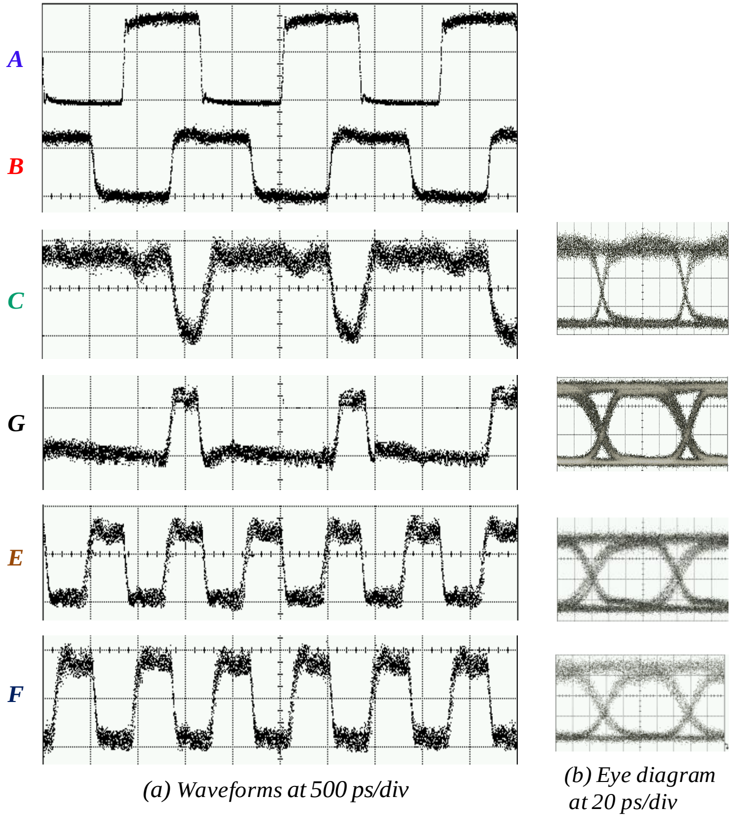


Fig. Oscilloscope waveform traces for all-optical logic gates and half adder

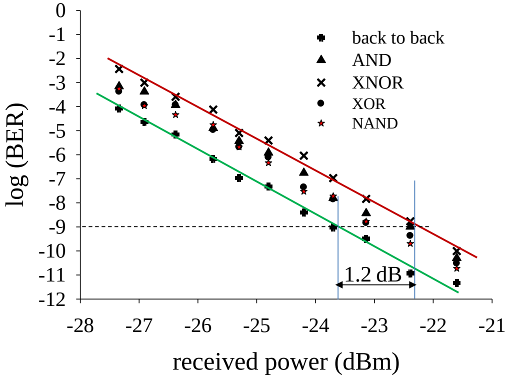


Fig. BER curves for all-optical logic gates

Ref: **Bikash Nakarmi,** M. Rakib-Uddin, and Y. H. Won, OSA Optics Express, July, 2011.

Digital Photonics: Combinational circuits

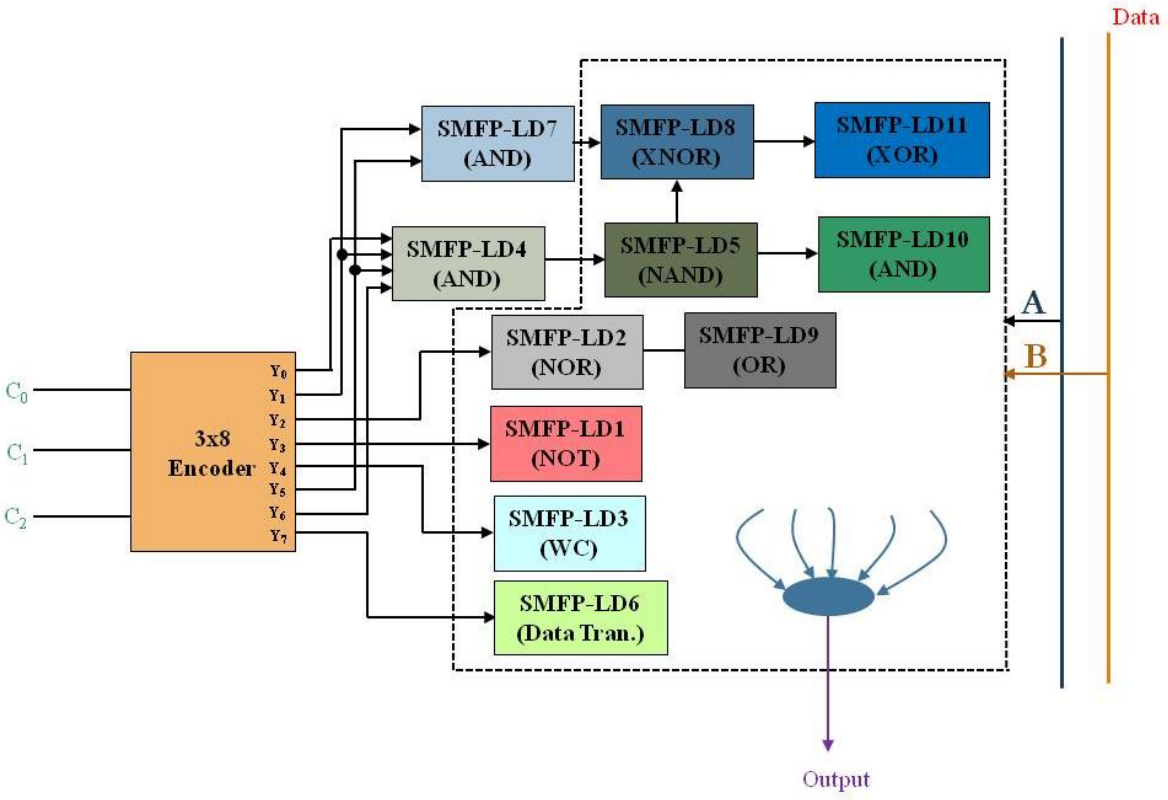


Fig. Proposition of Optical ALU

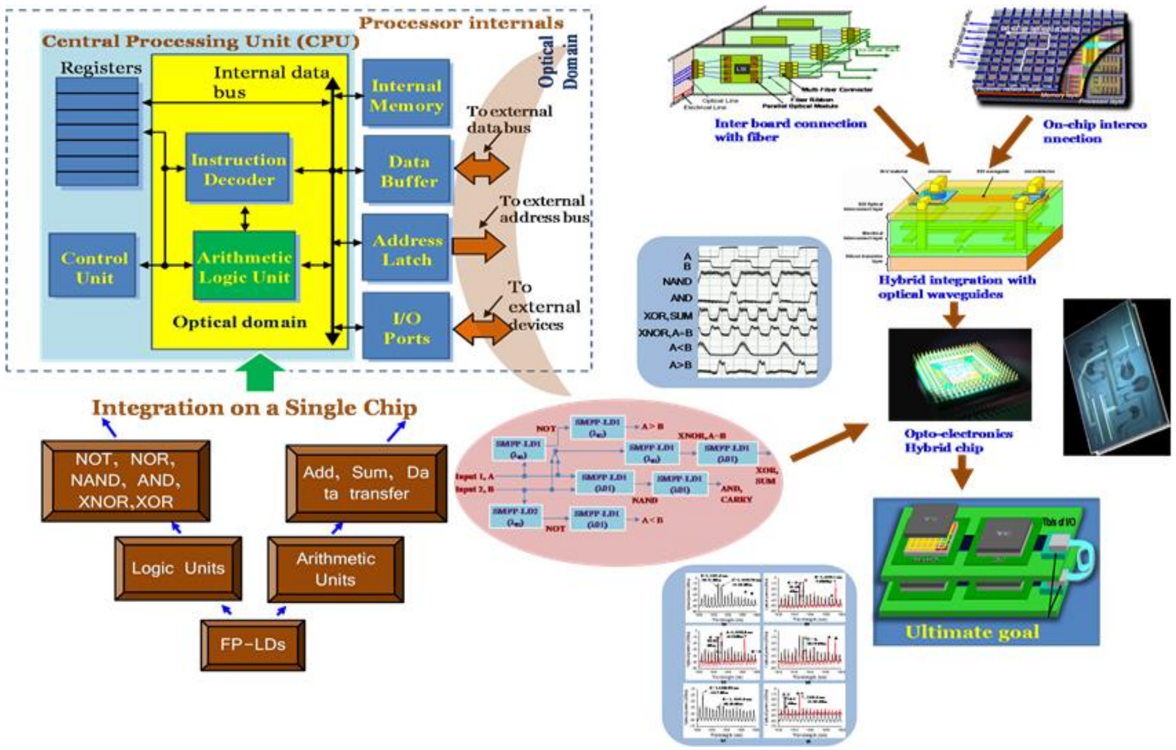


Fig. Overview of implementing Optical ALU & research developments map

Ref: **Bikash Nakarmi,** M. Rakib-Uddin, and Y. H. Won, OSA Optics Express, July, 2011.

Digital Photonics: Memory Accessing

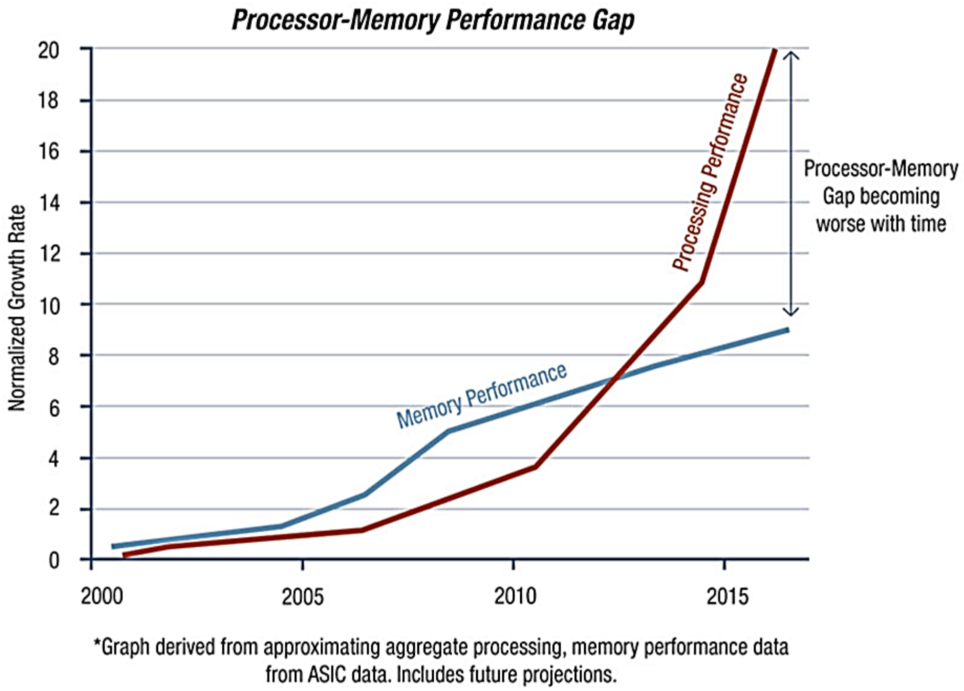


Fig. Processor and Memory performance Gap

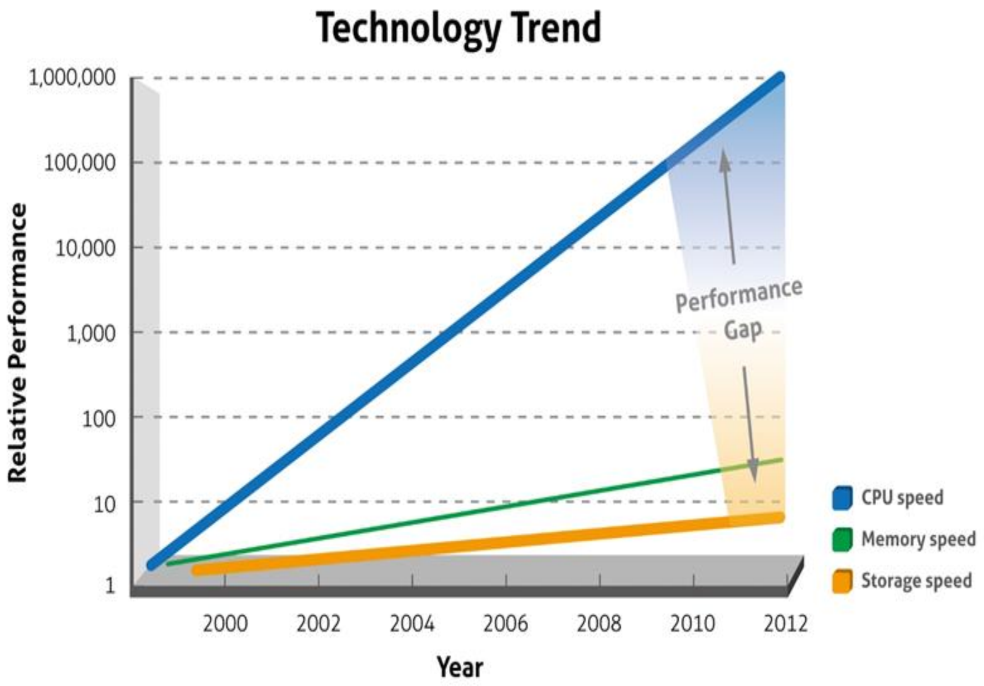


Fig. Technology trend

Digital Photonics: WDM Enabled Memory

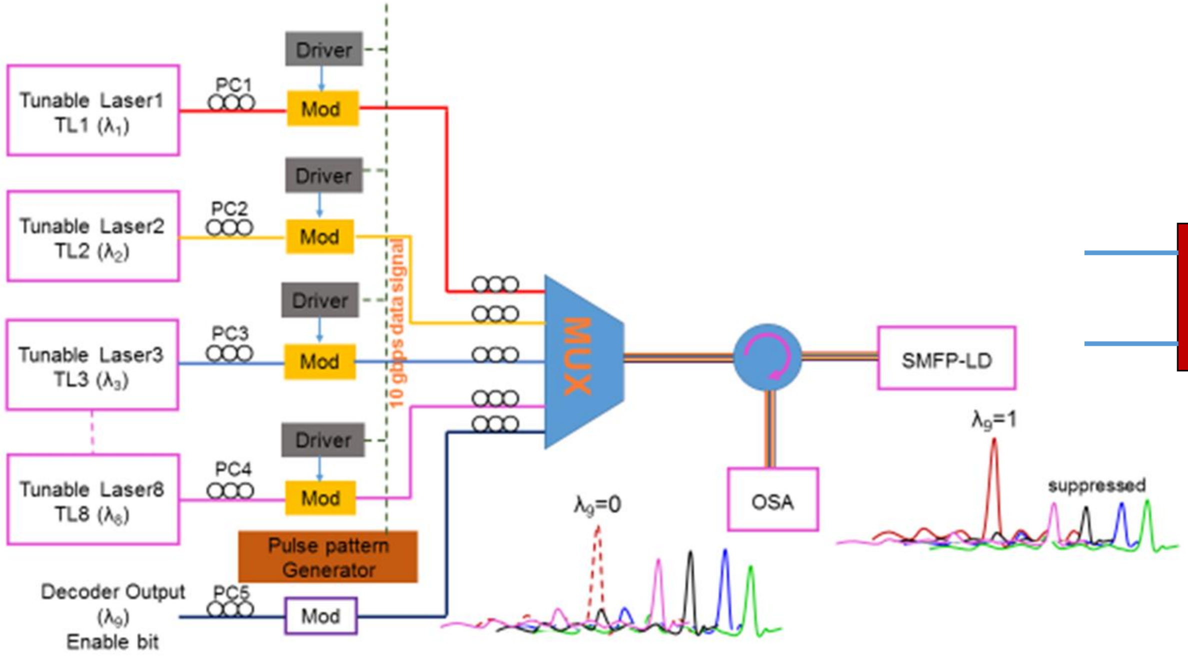


Fig. ACCESS SWITCH using SMFP-LDs

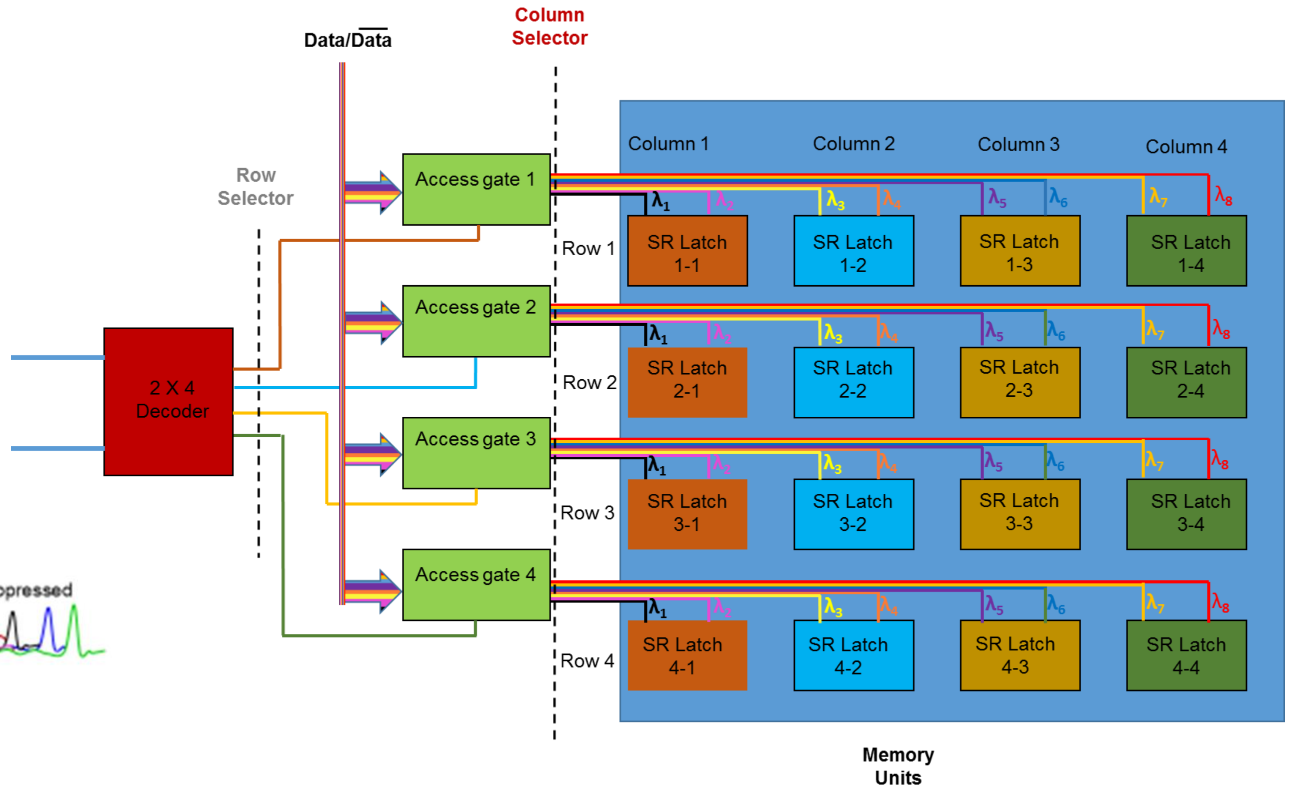
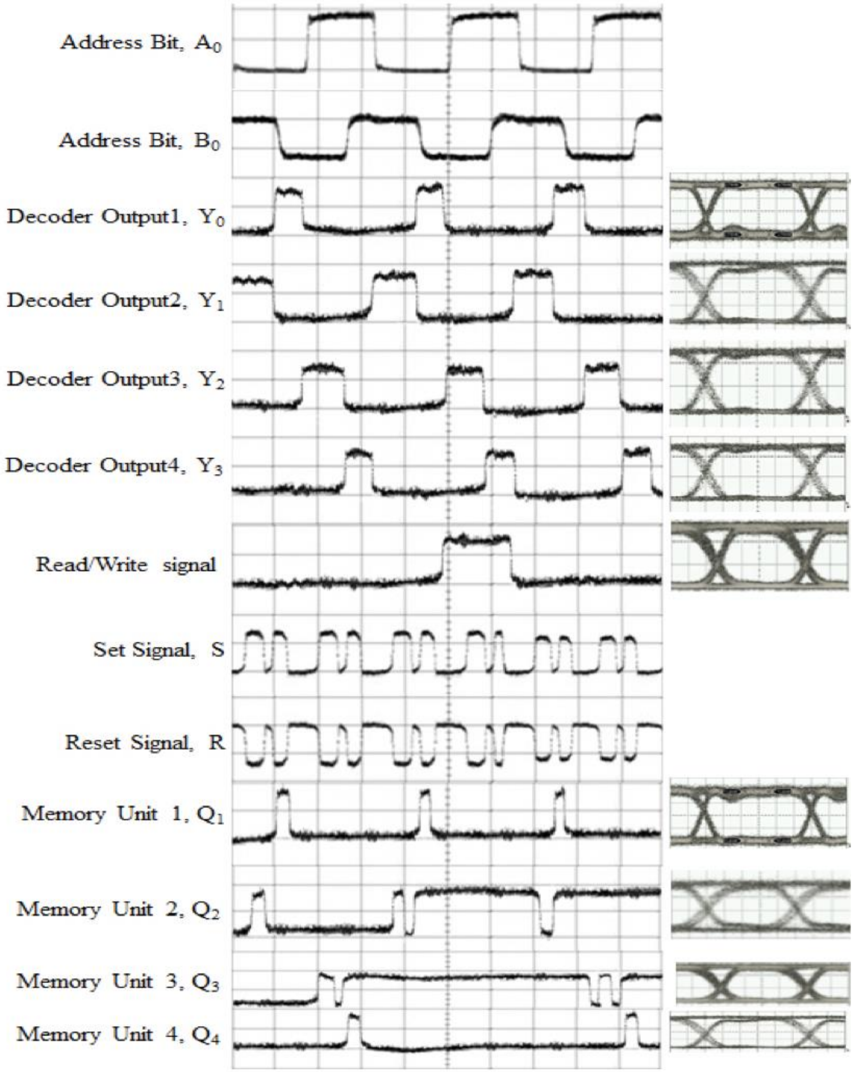


Fig. Conceptual diagram for the WDM enabled 4x4 memory accessing technique

Ref: **B Nakarmi,** TQ Hoai, and YH Won, X Zhang, Optics express 22 (13), pp 15424-15436, 2014
QH Tran, **B Nakarmi**, and YH Won, IEEE Photonics Journal 5 (2), pp. 7900811-7900811, 2013
B. Nakarmi, Ikechi Augustine, Chena Hao and Shilong Pan and et al. IEEE JSTQE, 2019

Digital Photonics: WDM Enabled Memory



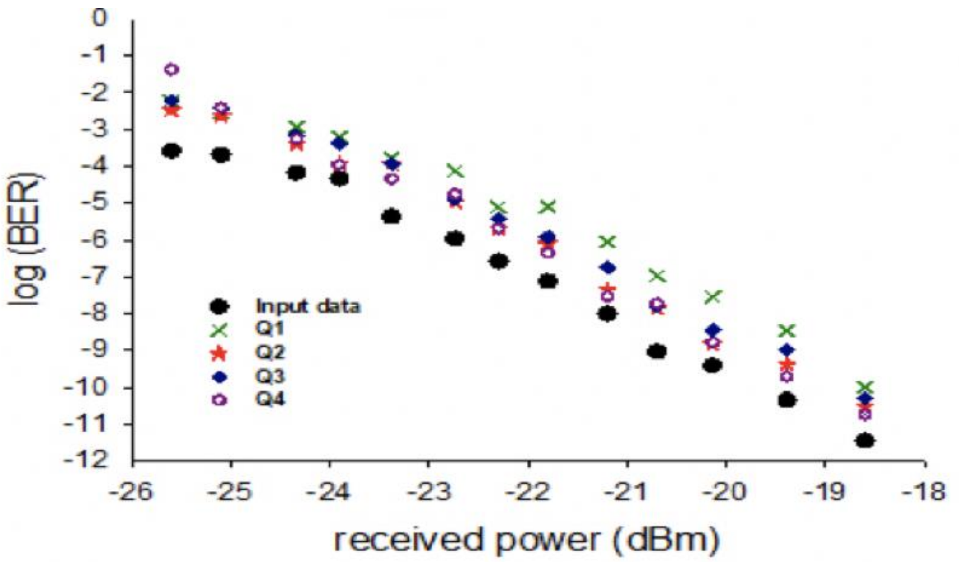
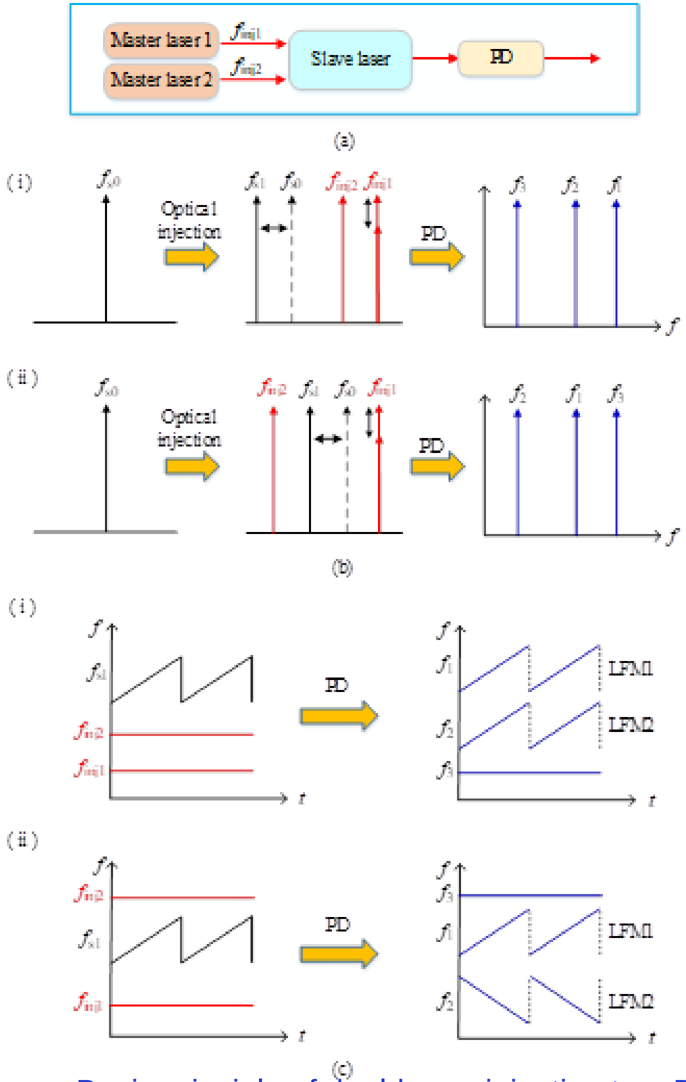
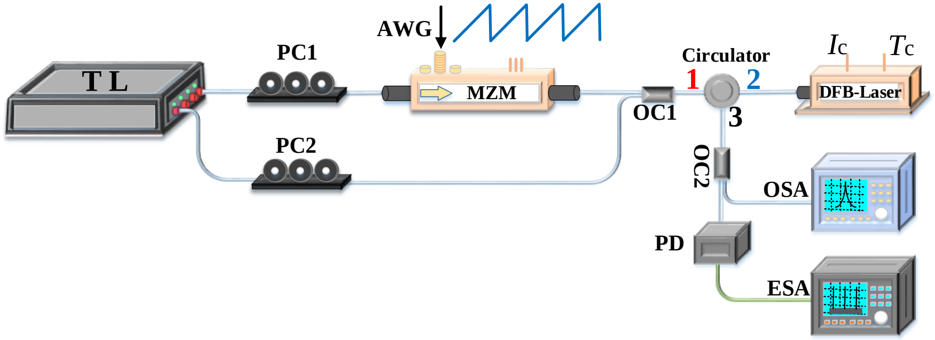


Fig. Output waveform for WDM enabled 4x4 memory accessing technique

Microwave Photonics : DFB-LD and Dual-LFM

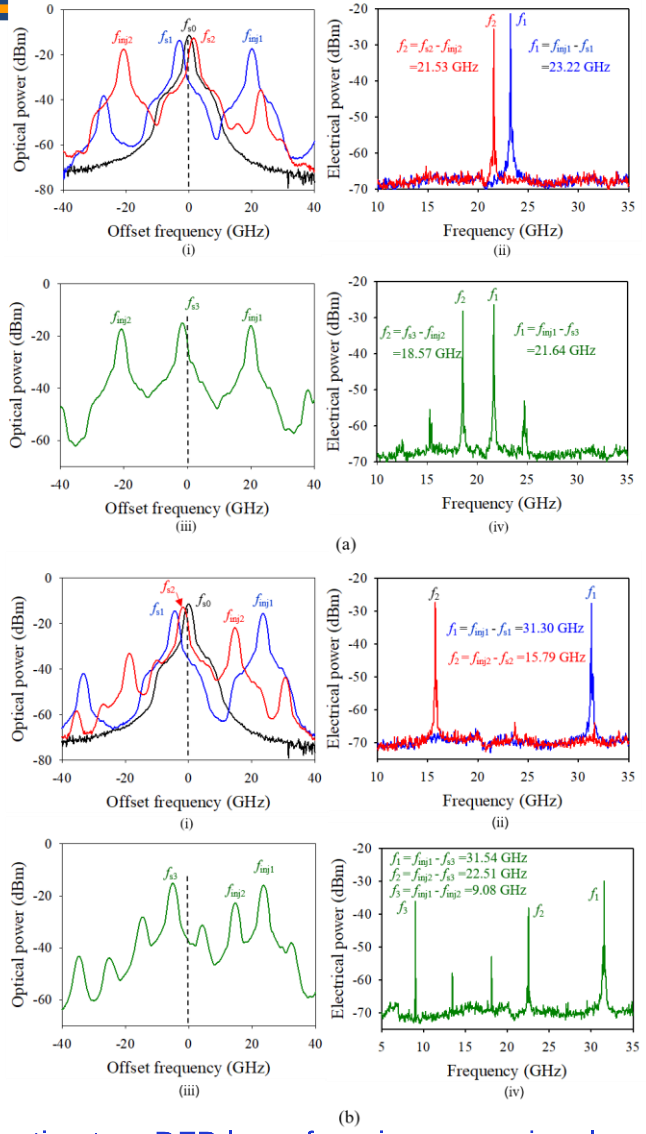


Basic principle of dual-beam injection to a DFB laser



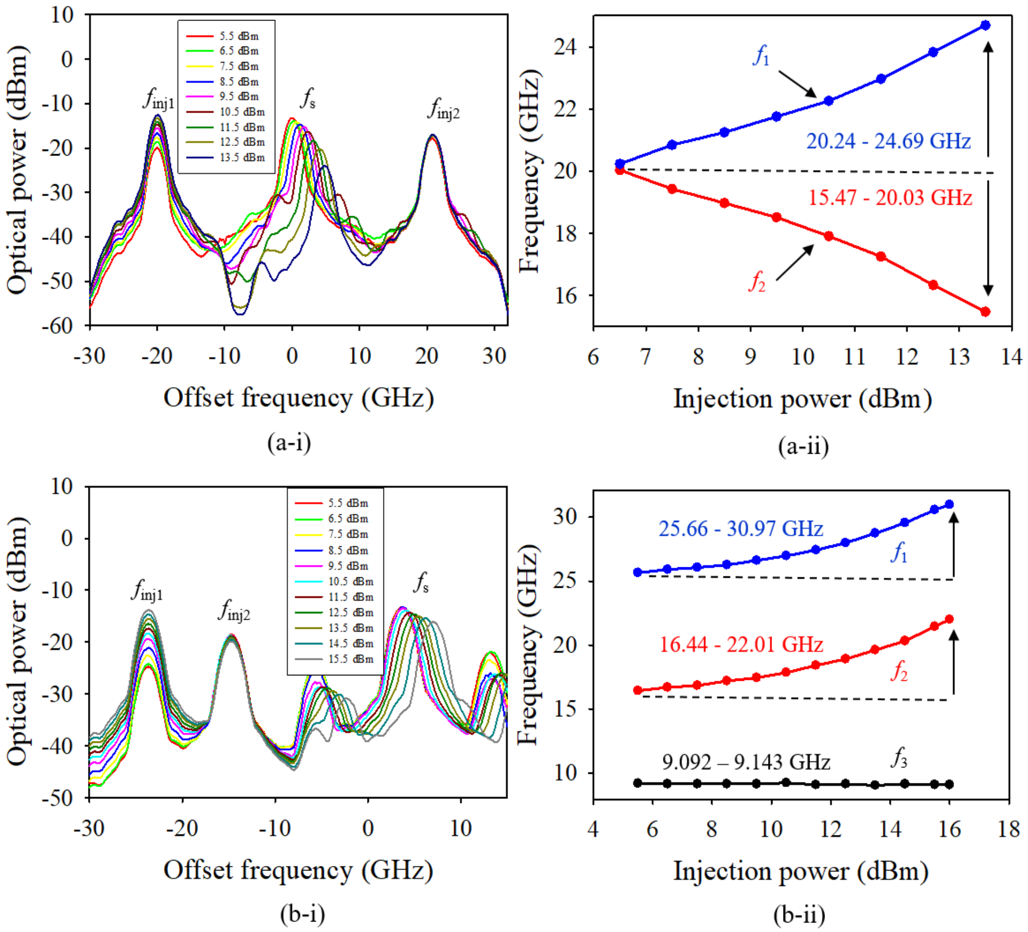
Ref: Hao Chen and et. al, submitted to JLT 2020

Experimental setup of dual-beam injection to a DFB laser for dual-LFM signal generation

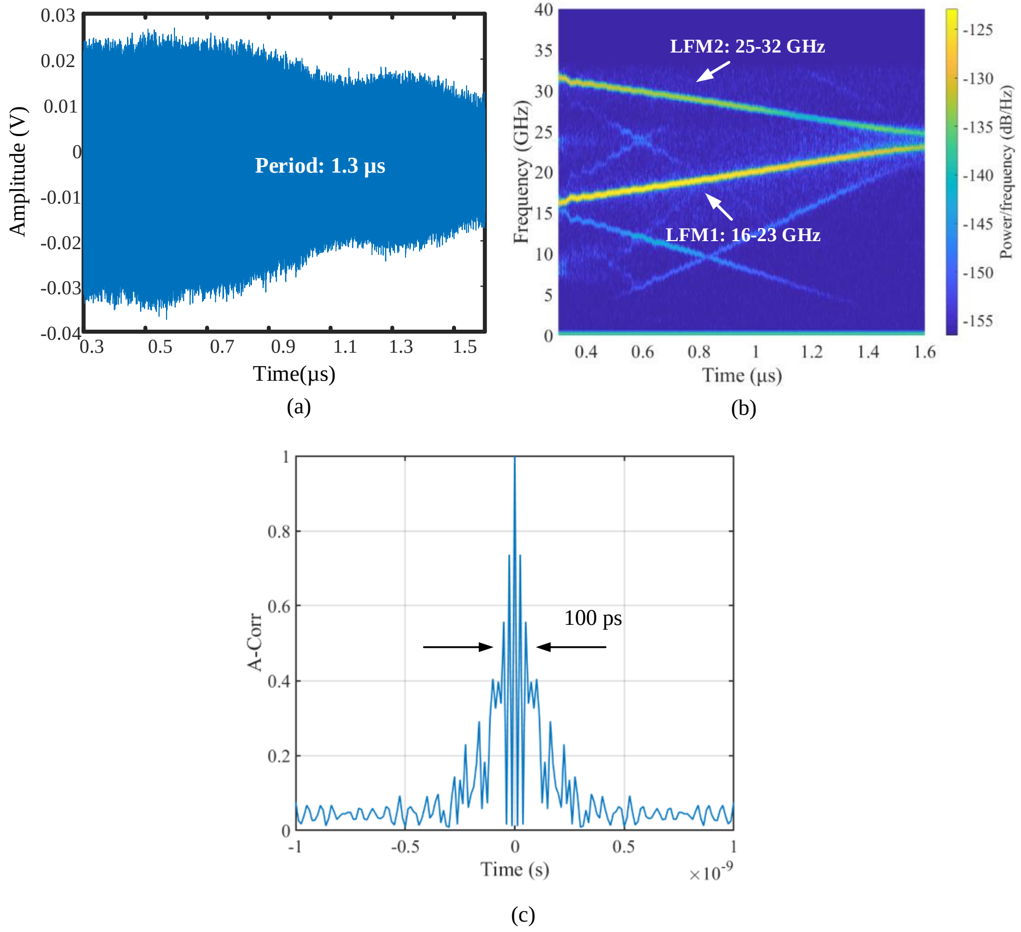


Experimental result of dual-beam injection to a DFB laser for microwave signal generation

Microwave Photonics : DFB-LD and Dual-LFM

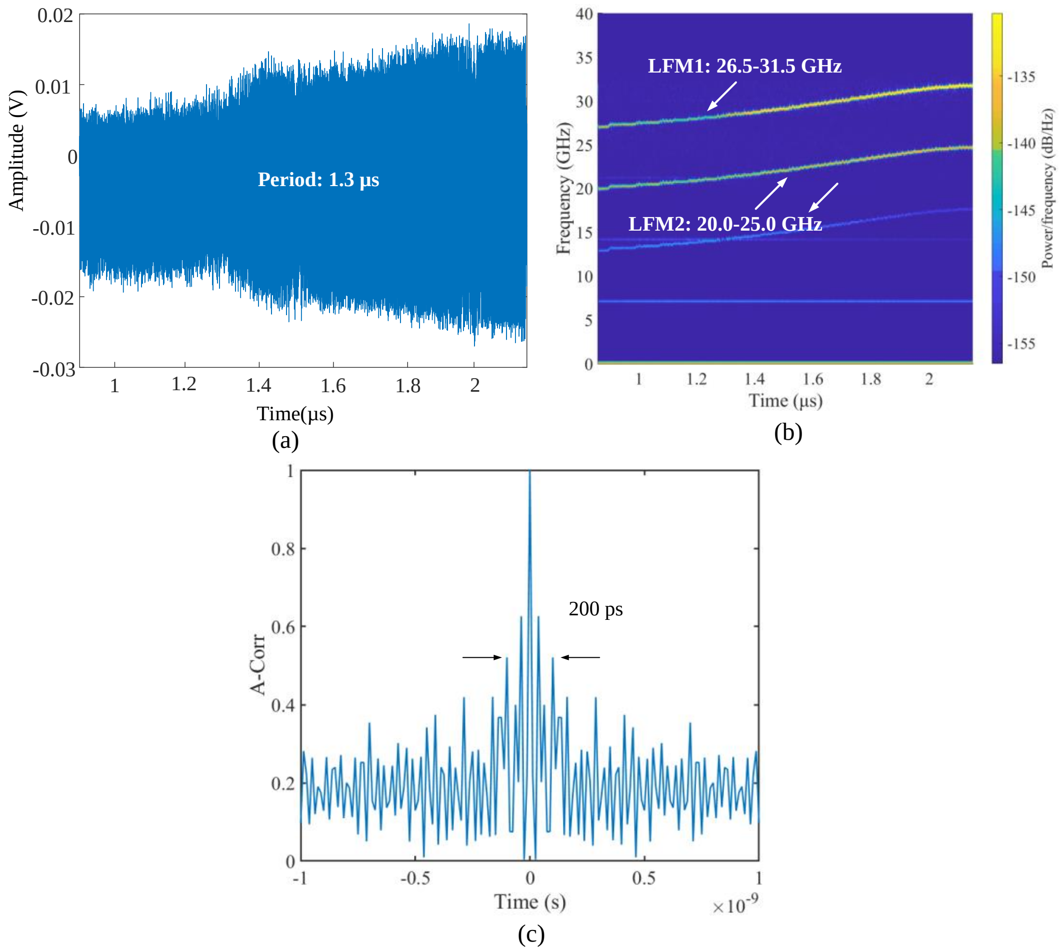


Optical injection with (a) opposite detuning frequencies and (b) both positive detuning frequencies for tunable microwave signals generation.

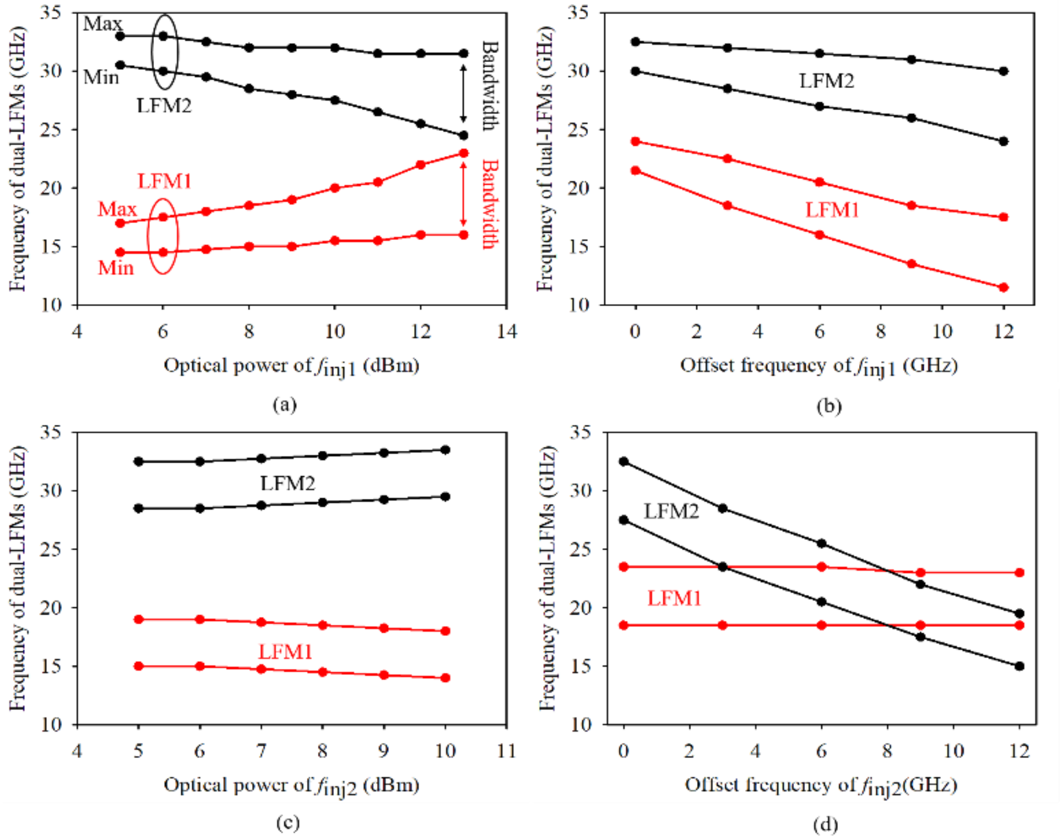


Temporal waveform, instantons frequency-time diagram and autocorrelation of Dual-LFM

Microwave Photonics : DFB-LD and Dual-LFM



Temporal waveform, instantons frequency-time diagram and autocorrelation of Dual-LFM



Tuanability analysis with opposite frequency detuning with change (a) optical power and (b) frequency of finj1 (c) optical power and (d) frequency of finj2.