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Deriving Broadband Laser Ranging Parameters from First Principles

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Outline

Basic layout of BLR (Mach-Zehnder plus fiber dispersion)

Use Working Group recommendations as a guideline

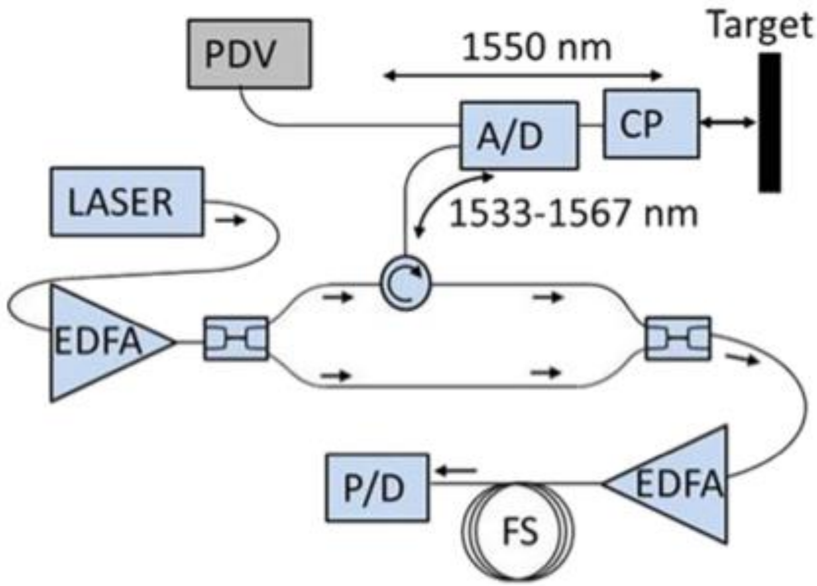
Determine wavelength spectra from Mach-Zehnder

Determine fiber lengths

Compare to an as-built system

Sketch of Broadband Laser Ranging Diagnostic

(Figure from La Lone, et al., *Rev. Sci. Instrum*. **86** (2015) 023112.)



The BLR is multiplexed with a PDV in this figure.

The laser is short pulse, broadband.

One leg of the Mach-Zehnder (MZ) varies in length as the surface moves closer to the probe.

The long fiber spool (FS) provides the necessary dispersion.

Ed Daykin hosted a Broadband Laser Ranging Design Physics Working Group, December 7–8, 2015

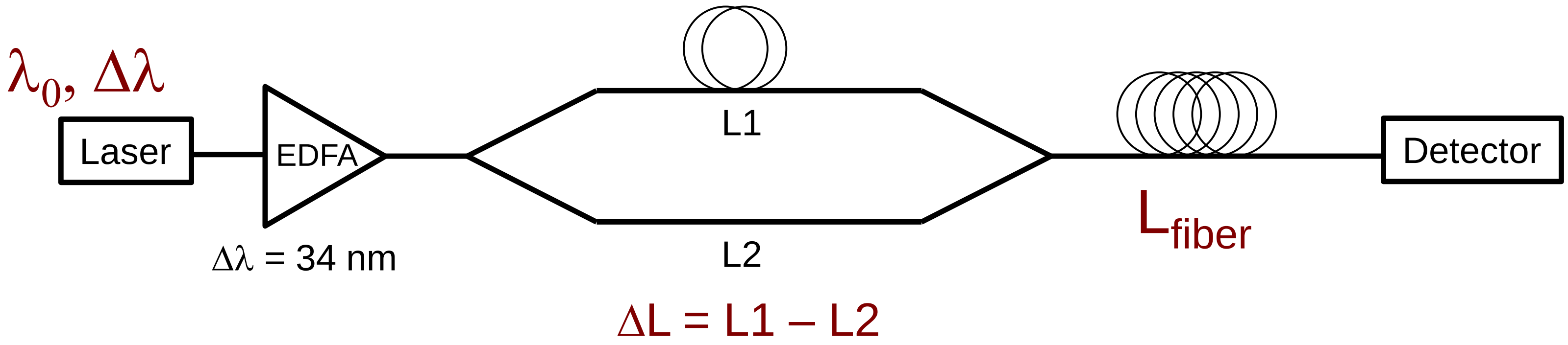
They recommended approximate parameters for the BLR that would be useful for NWL applications.

		This Study			
Parameter	WG	OTS1	OTS2	OTS3	OTS4
Digitizer (GS/s)		50	50	50	50
Digitizer (ps/pt)		20	20	20	20
N(fft)		1024	2048	4096	8192
Laser wavelength (nm)	1560	1550	1550	1550	1550
Laser linewidth (nm)	20	20	20	20	20
Laser interval (ns)	50	20.48	40.96	81.92	163.84
Laser rep rate (MHz)	20	48.8	24.4	12.2	6.1
Temporal spread (ns)		20.48	40.96	81.92	163.84
Sensitivity (mm/GHz)					
Fiber length (km)	200				

Note: Laser wavelength range = 1540–1560 nm. EDFA is 1528–1562 nm.

(red indicates calculated values)

The basic BLR geometry is laser, MZ, fiber



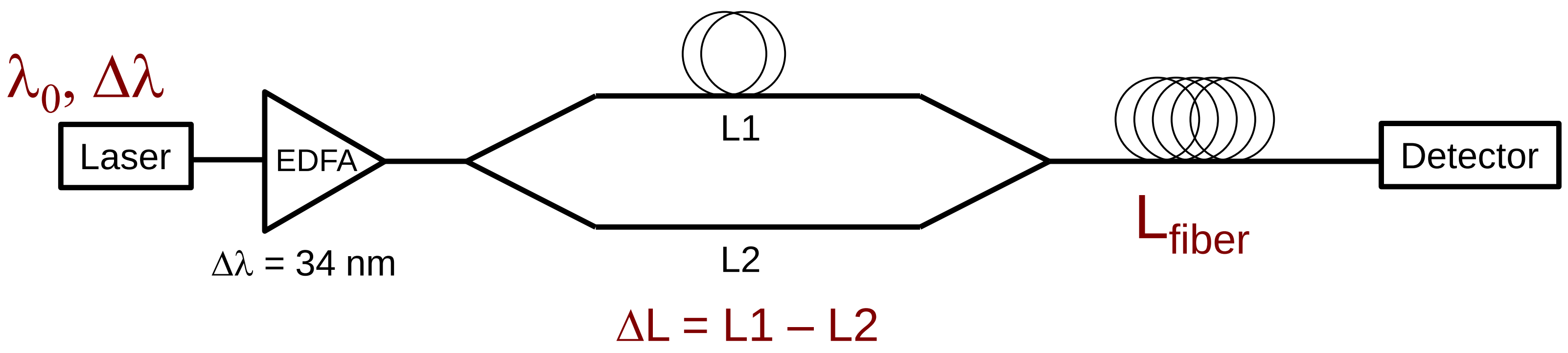
EDFA has a 34 nm pass band

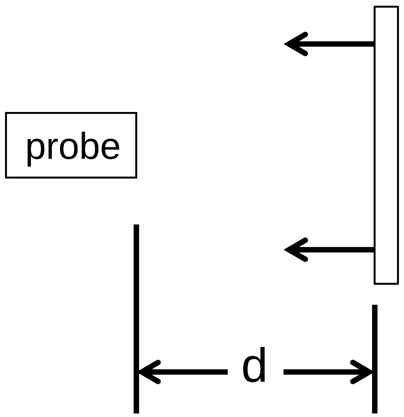
(e.g., Lightwaves2020 operating range is 1528 to 1562 nm.)

We will first look at the MZ interferometry to derive the sensitivity.

Then we will look at L_{fiber}.

The Mach-Zehnder generates a peak in the wavelength spectrum when L1 – L2 = integer number of wavelengths





Round trip = 2d
so look for

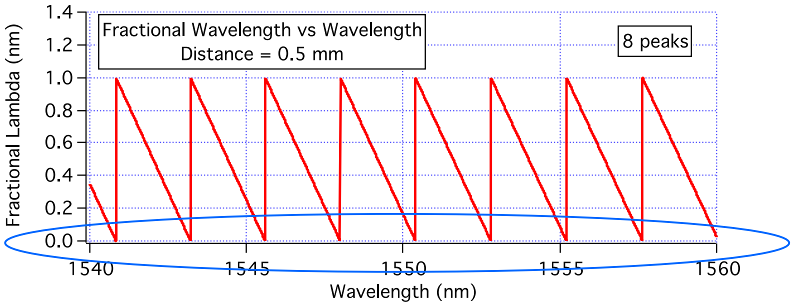
$L1 - L2 = n\lambda = 2d$

Note: L1 = L2 is defined as the "balance point."

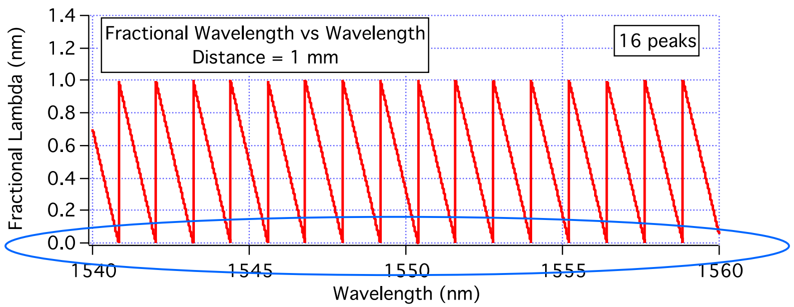
Build a spreadsheet to look for integer number of wavelengths at different distances

List wavelengths from 1540 to 1560 nm in 0.001 nm increments.
Choose a range of distances to measure with the BLR.
Calculate the number of wavelengths in 2d. Get xxx.yyy wavelengths.
Count how many wavelengths have yyy = 0 (constructive interference).

Look at plots of yyy vs. wavelength for different distances.



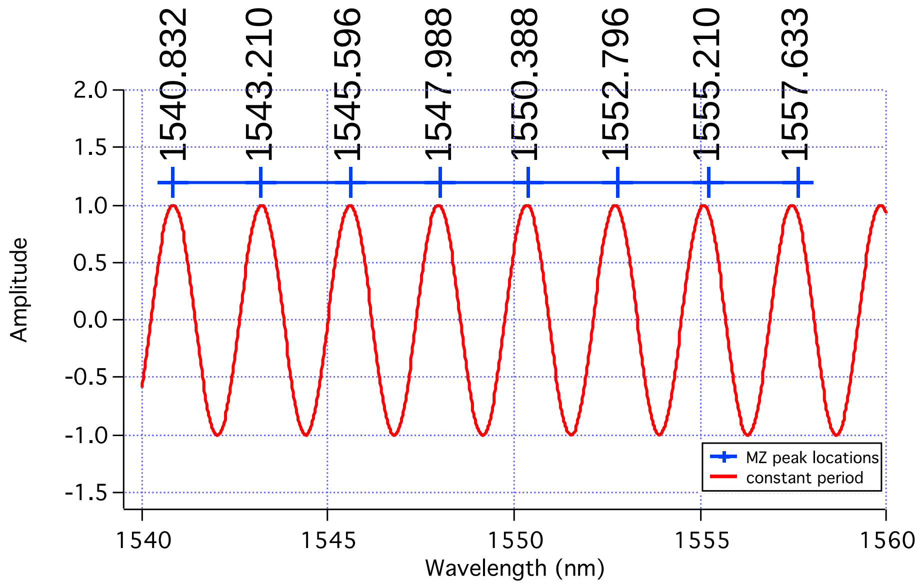
Distance = 0.5 mm
gives 8 peaks
(almost 9).



Distance = 1 mm
gives 16 peaks
(almost 17).

Constructive and destructive interference in the MZ generates a wavelength spectrum at each distance

Distance = 0.5 mm gives 8 peaks in the wavelength spectrum.
(1st peak is at 1540.832 nm.)



The waveform (red) has a constant period given by the first two wavelengths.

Sending this wavelength spectrum through the dispersive fiber generates the frequency vs. time data of the BLR.

Note: Wavelength spacing from the MZ is not constant.
This is a source of chirp in the data.

Calculate the number of peaks generated within 1540–1560 nm at different distances

Distance (mm)	Number Peaks
0.5	8
1	16
2	33
5	83
10	167
20	333
25	416
50	833
100	1665
200	3330

Note that the number of peaks vs. distance depends upon only the interferometry in the MZ.

The BLR frequency is determined by how many peaks arrive at the detector within each time interval.

This determines the sensitivity of the BLR in units of mm/GHz.

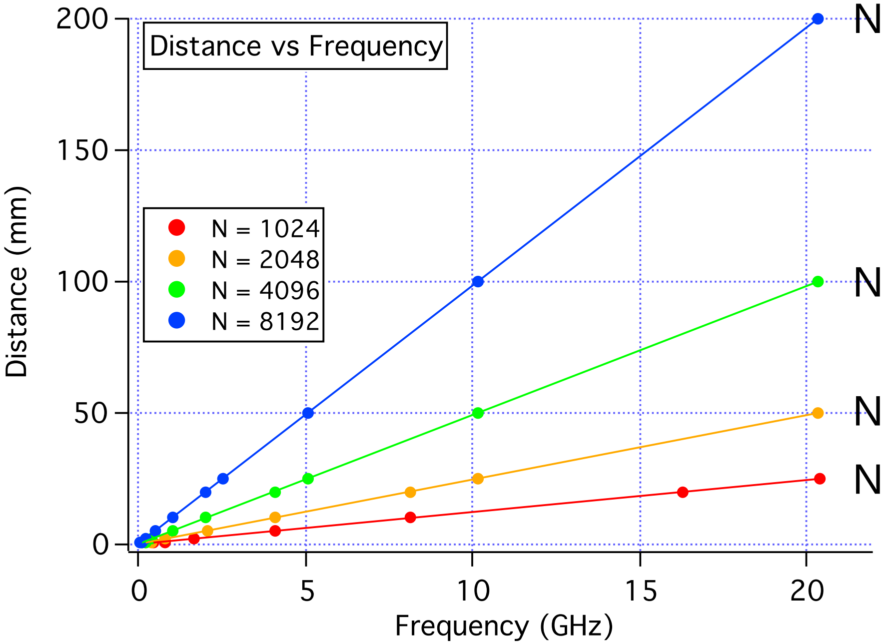
(“Distance” is with respect to the balance point of the MZ.)

Calculate the BLR frequency for different step sizes and different distances

BLR frequency (GHz) = NumberPeaks/TemporalSpread(ns)

Distance (mm)	Number Peaks	Temporal Spread (ns)			
		20.48	40.96	81.92	163.84
0.5	8	0.39	0.20	0.10	0.05
1	16	0.83	0.42	0.21	0.10
2	33	1.61	0.81	0.40	0.20
5	83	4.05	2.03	1.01	0.51
10	167	8.15	4.08	2.04	1.02
20	333	16.26	8.13	4.06	2.03
25	416	20.31	10.16	5.08	2.54
50	833		20.34	10.17	5.08
100	1665			20.32	10.16
200	3330				20.32

Plot distance from balance point vs. frequency to obtain BLR sensitivity in [mm/GHz]



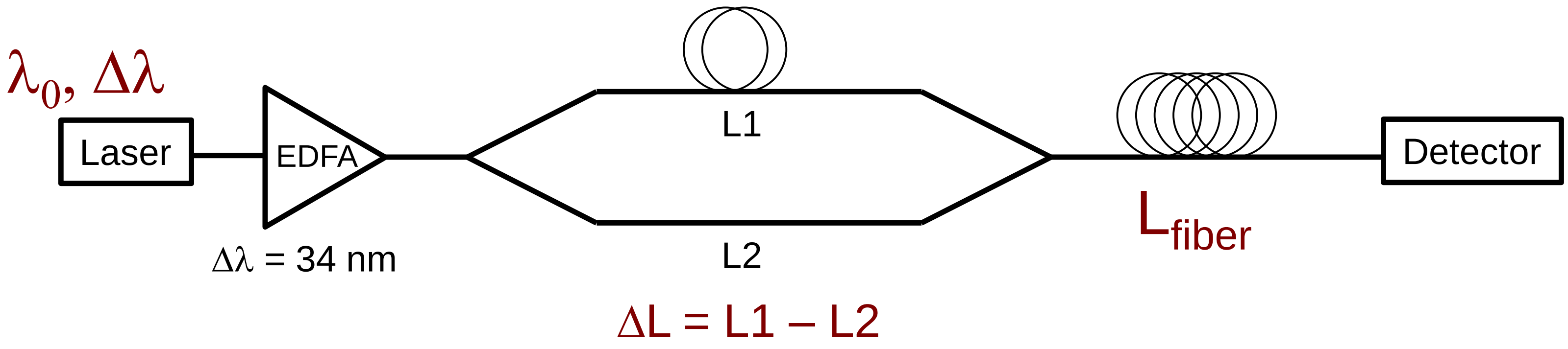
N = 8192, slope = 9.84 mm/GHz

N = 4096, slope = 4.92 mm/GHz

N = 2048, slope = 2.46 mm/GHz

N = 1024, slope = 1.23 mm/GHz

Now look at fiber dispersion to spread the MZ wavelength spectrum in time at the detector



The temporal spread is calculated from the fiber dispersion, the laser linewidth, and the fiber length:

$$T[ns] = D(1550)[ps/(nm\text{-}km) * \Delta\lambda\ [nm] * L_{fiber}[km] * 1000$$

$$L_{fiber}[km] = \frac{T[ns]}{D(1550)[ps/(nm\text{-}km] * \Delta\lambda\ [nm] * 1000}$$

Dispersion for Corning SMF-28 fiber

Fiber dispersion (from Corning SMF-28 spec sheet)

Dispersion

Zero Dispersion Wavelength (λ_0):
1302 nm $\leq \lambda_0 \leq$ 1322 nm

Zero Dispersion Slope (S_0):
$\leq$ 0.092 ps/(nm²•km)

$$\text{Dispersion} = D(\lambda): \approx \frac{S_0}{4}\left[\lambda - \frac{\lambda_0^4}{\lambda^3}\right] \text{ps/(nm•km)},$$

for 1200 nm $\leq \lambda \leq$ 1600 nm

λ = Operating Wavelength

$$D(l) = \frac{S_0}{4}\left[l - \frac{l_0^4}{l^3}\right] ps/(nm * km)$$

$$D(1550) = \frac{0.092}{4}\left[1550 - \frac{1313^4}{1550^3}\right]$$

D(1550) = 17.29 ps/(nm-km)

Note: Dispersion varies with wavelength,
which is a 2nd source of chirp in the BLR data.

We can now calculate the fiber length for each case

$$L_{fiber}[km] = \frac{T[ns]}{D(1550)[ps/(nm\text{-}km)] * \Delta\lambda\ [nm] * 1000}$$

Temporal spread T[ns] = Step Size

D(1550) = 17.29 ps/(nm-km)

$\Delta\lambda$ = 20 nm

N	Step Size (ns)	Fiber Length (km)
1024	20.48	59
2048	40.96	118
4096	81.92	237
8192	163.84	474

Final BLR parameters and comparison with an actual system

Parameter	WG	OTS1	OTS2	OTS3	OTS4	La Lone
		This Study				
Digitizer (GS/s)		50	50	50	50	50
Digitizer (ps/pt)		20	20	20	20	20
N(fft)		1024	2048	4096	8192	
Laser wavelength (nm)	1560	1550	1550	1550	1550	1570
Laser linewidth (nm)	20	20	20	20	20	17
Laser interval (ns)	50	20.48	40.96	81.92	163.84	80
Laser rep rate (MHz)	20	48.8	24.4	12.2	6.1	12.5
Temporal spread (ns)		20.48	40.96	81.92	163.84	65
Sensitivity (mm/GHz)		1.23	2.46	4.92	9.84	4.5
Fiber length (km)	200	59	118	237	474	200

(red indicates calculated values)

Summary

Use first principles to derive the parameters for four BLR systems.

The Mach-Zehnder determines the wavelength spectrum at each distance.

The wavelength spectra and temporal spread determine the sensitivity in [mm/GHz].

The temporal spread determines the fiber length.

The parameters obtained agree well with an as-built system.

Two sources of chirp are noted, but not considered here.