Optical filter assembly for interplanetary optical communications

Y. Chen and H. Hemmati

Jet Propulsion Laboratory

California Institute of Technology

OUTLINE

- Objective and rationale
- Existing filter technologies
- Requirements
- Options
- Lab experiment results
- Conclusions

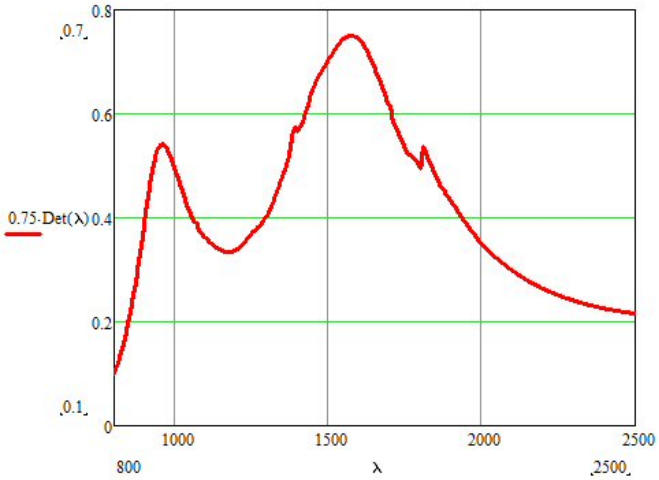
OBJECTIVE AND RATIONALE

Objectives:

- Develop narrowband filter for Deep-space Optical Terminals (DOT) Ground Terminal
- Validate in laboratory and in the field
- Remove uncertainty on actual values for filter's transmission and filtering bandwidth

Rationales:

- Background can easily overwhelm signal in a deep space link
- Wide range of wavelengths need to be eliminated since nanowire detectors (NbN and a-W_xSi_{1-x}) have wide spectral responsivity
- Off-the-shelf filters meeting DOT's requirements are not available



Superconducting amorphous tungsten–silicon alloy nanowire detector response

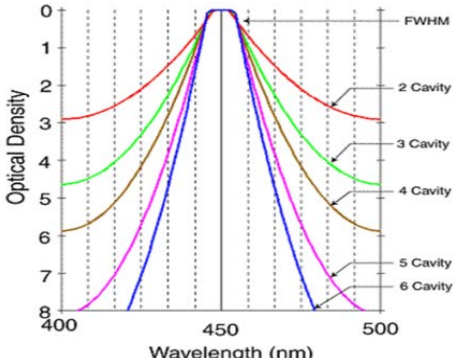
REQUIREMENTS

- Based on the flight terminal transmitter and orbital operation requirements, ground receiver design and Earth atmospheric effect, the ground receiver filter requirements are derived and shown in the Table below

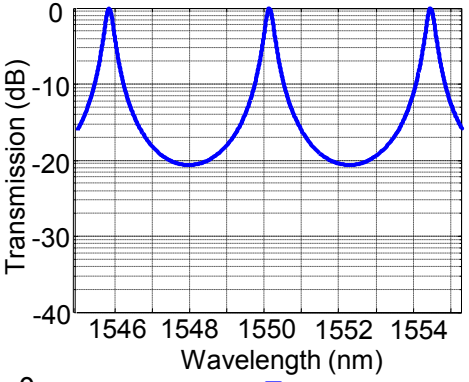
Parameters	Requirement	Justification
Center wavelength (nm)	~1550	DOT requirement
Tunability (pm)	±150	• ±80 pm, from expected post-launch shift (10% ITU grid of 100GHz) • ±40 pm, from max Doppler shift • ±10 pm (=0.1*dλ/dT), from laser chamber temperature drift of 0.1ºC • ±20 pm, assumed margin
Bandwidth (noise equivalent - nm)	0.17±0.03	DOT requirement
Transmission efficiency (%)	>80	DOT requirement
Minimum clear aperture (mm)	>23	To cover 2 to 12m telescope apertures; and FOV=50 μrad of atmospheric seeing for daytime operation (DOT require. L3-GLR3.8)
Acceptance angle (FOV - degree)	≥1.5	Same as above
dλ/dT (pm/ºC)	>10 <85	Not too small requiring large temperature variation for tuning, but not too large causing big change with small temperature variation (instability)
Out-of-band rejection range (nm)	1,000 to 3,000	Nanowire detector has response over all the wavelengths with peak around 1550nm. BK7 and silica will be placed in front of the detector to remove noise/unwanted signals below 1μm and above 3μm
Ratio of integrated power within the signal band to that outside the signal band	>3 or 10	Contributions (radiance, stray light, noise) outside the band can be comparable to those within the band, because photon counting detectors follow Poisson statistics
Operating temperature (ºC)	5 to 80	Temperature likely experienced by filter
Surface quality (scratch & dig)	40-10	Negligible scattering
Surface flatness (at 633nm)	<λ/4	Negligible scattering
Polarization	Meet spec for any polarization	Depolarization/polarization must be less than 1%

EXISTING FILTER TECHNOLOGIES

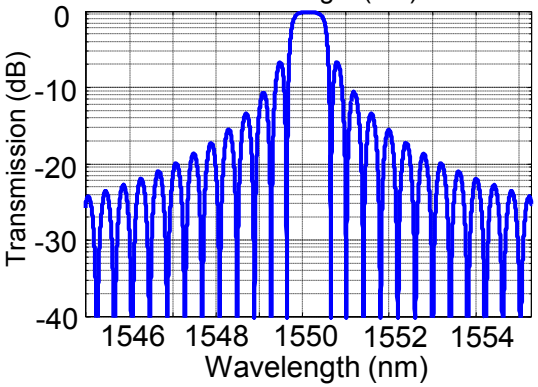
- **Dielectric (interference) filter**
  - Can be designed for high quality filtering
  - Difficulty to fabricate for uniformity with high transmission efficiency
  - Typically work only over ~200nm



- **Fabry-Perot Etalon (FPE)**
  - Relatively easy to make
  - Free Spectral Range is a limitation



- **Volume Bragg Grating (VBG)**
  - High quality filtering within the transmission band
  - Low suppression outside transmission band
  - Limited by side lobes outside the transmission band



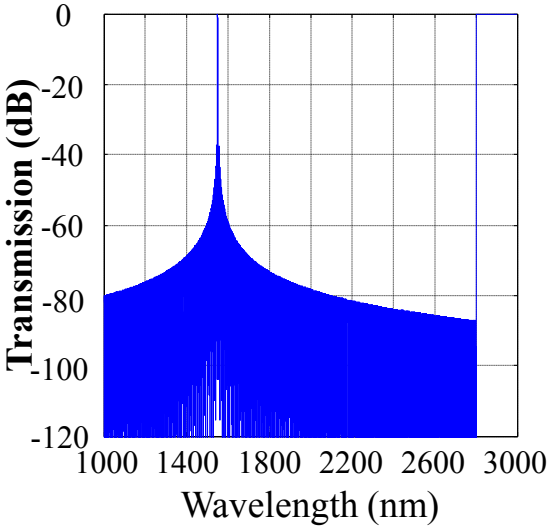
A Single Filter Technology DOES NOT Meet The Requirements

CHARACTERISTICS OF DIFFERENT OPTIONS

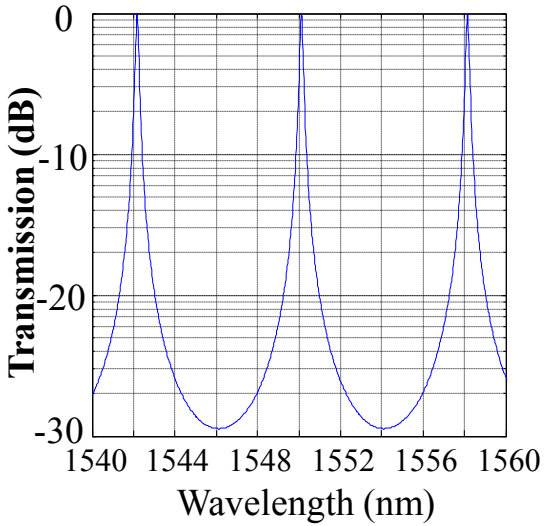
Parameters	Requir.	A) #1 (VBG)	B) #2 (VBG)	C) #1 (FEP)	D) #2 (FEP)	E) (Interference)	F) (Wide band)	G) (Long wave blocking)	Option 1 A+C+G	Option 2 A+E+G	Option 3 E+F+G	Option 4 C+F+G
Center wavelength (nm)	1550	1550	1550	1550	1550	1550	1550	1550	1550	1550	1550	1550
Tunability (pm)	±150	±150	±150	±150	±150	±150	N/A	N/A	±150	±150	±150	±150
Bandwidth (nm)	0.17	0.2	0.15	0.17	0.17	0.17	3	>50	0.17	0.17	0.17	0.17
Transmission efficiency (%)	>80	96	93	95	97	>80 (85)	95	95	87 (-0.6dB)	78 (-1.08dB)	77 (-1.14dB)	86 (-0.66dB)
Minimum clear aperture (mm)	>23	23	23	23	23	23	23	23	23	23	23	23
Acceptance angle (FOV - mrad)	>26	24	24	24	24	24	24	24	24	24	24	24
$d\lambda/dT$ (at 0.1°C tem. variation)	>9pm/°C <85 pm/°C	15	15	9	9	13	N/A	N/A	15/9	15/13	13	9
Out of band rejection range (nm)	850-3000	800-2800	800-2800	4	4	1380-1770	850-1780	1750-3000	850-3000	850-3000	850-3000	850-3000
Out of band rejection ratio	>10	<1	<1	<1	<1	<1	<1	<1	7	12	3.7	1
Price ($K)		30.9	36.4	14.3	14	66.4	0.622	3.5	48.7	100.8	70.522	18.122
Lead time (Weeks)	16	8-12	8-12	10-12	5	16	1	8	10-12	16	16	10-12
Required ovens	1	1	1	1	1	1	0	0	2	2	1	1

OPTION 1

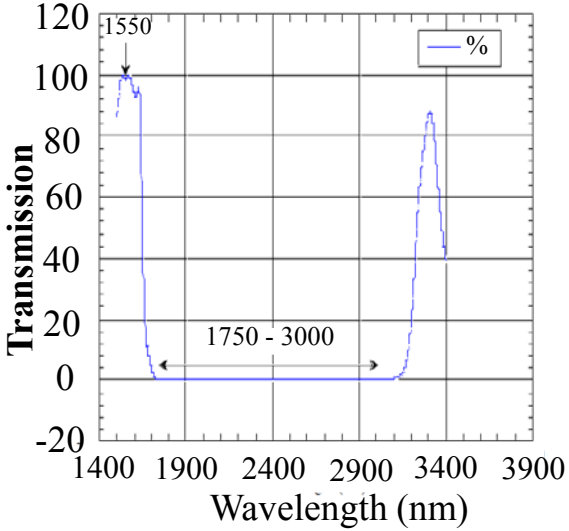
A: VBG



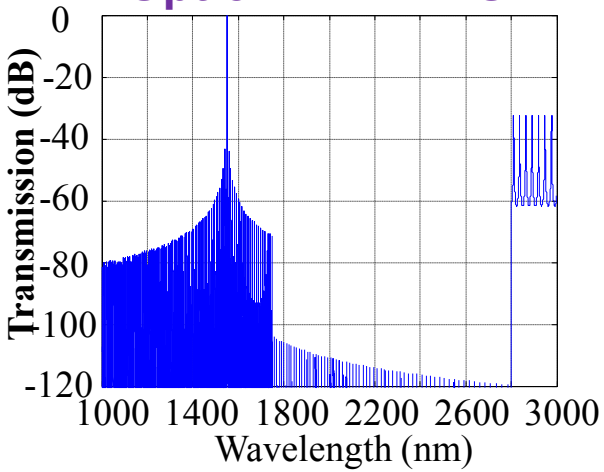
C: FP Etalon



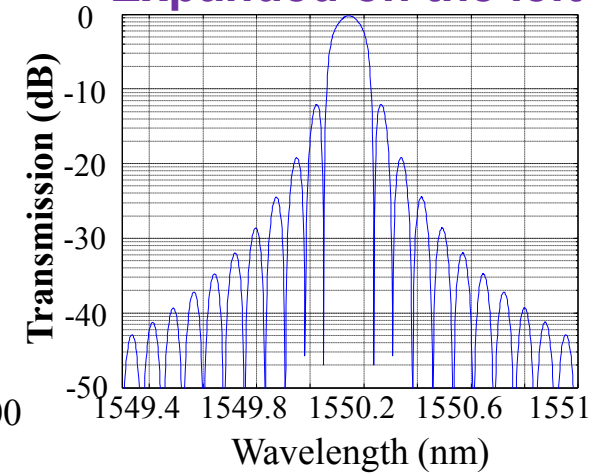
G: Long wave blocking filter



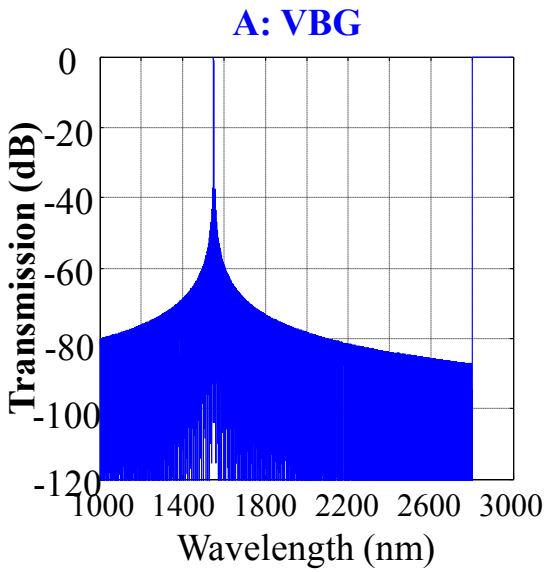
Option 1: A+C+G

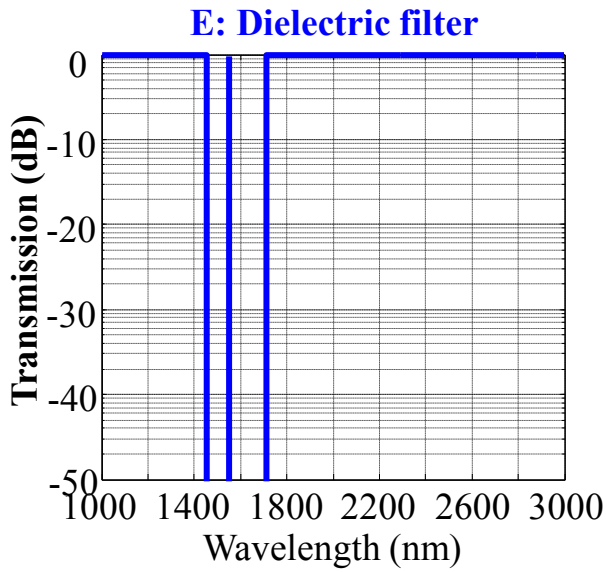


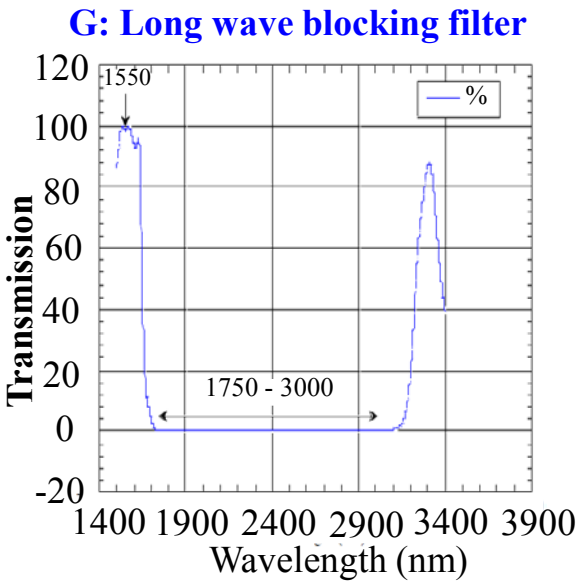
Expanded on the left

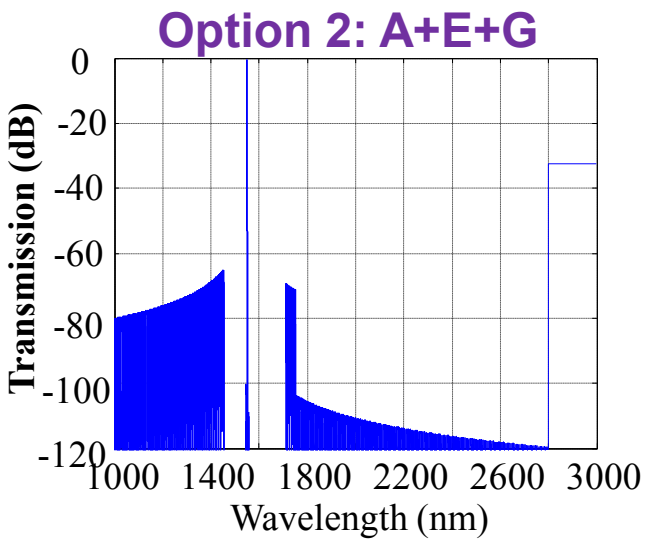


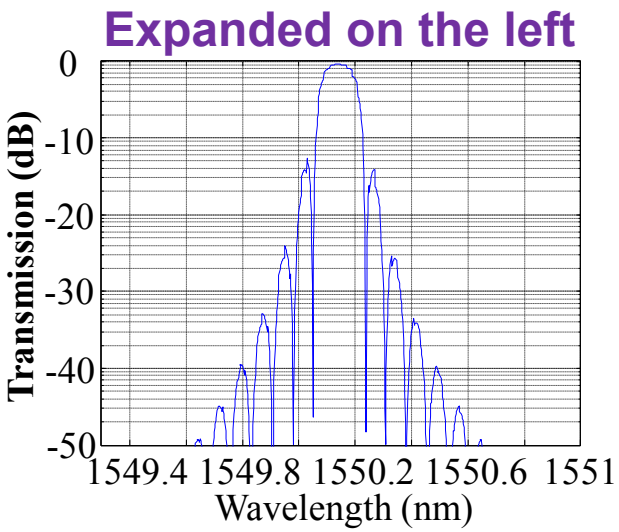
OPTION 2


A: VBG
Transmission (dB)
0
-20
-40
-60
-80
-100
-120
1000 1400 1800 2200 2600 3000
Wavelength (nm)


E: Dielectric filter
Transmission (dB)
0
-10
-20
-30
-40
-50
1000 1400 1800 2200 2600 3000
Wavelength (nm)

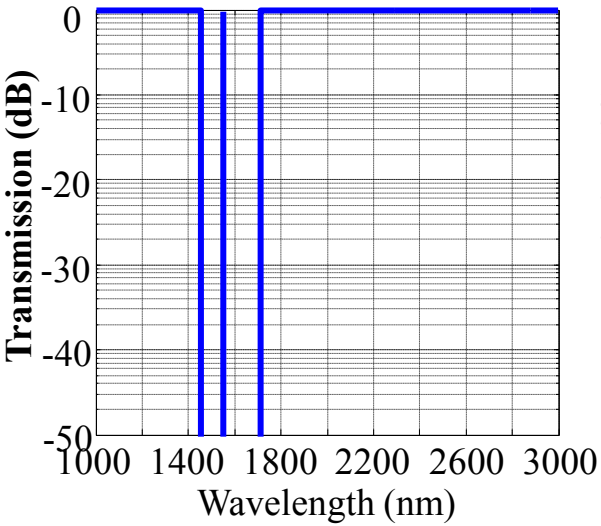

G: Long wave blocking filter
Transmission
120
100
80
60
40
20
0
-20
1550
%
1750 - 3000
1400 1900 2400 2900 3400 3900
Wavelength (nm)


Option 2: A+E+G
Transmission (dB)
0
-20
-40
-60
-80
-100
-120
1000 1400 1800 2200 2600 3000
Wavelength (nm)

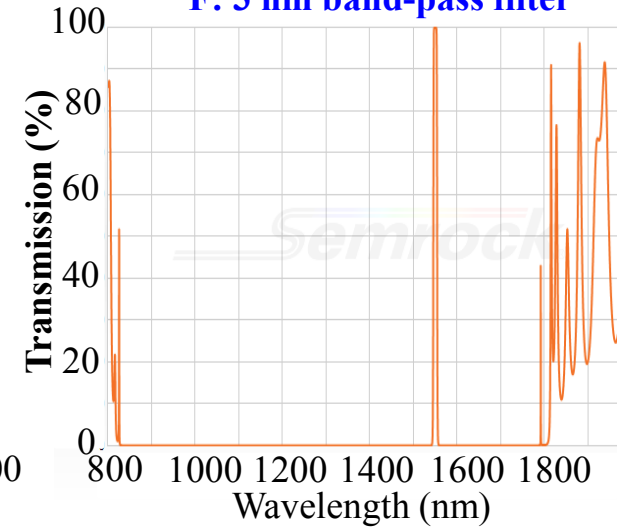

Expanded on the left
Transmission (dB)
0
-10
-20
-30
-40
-50
1549.4 1549.8 1550.2 1550.6 1551
Wavelength (nm)

OPTION 3

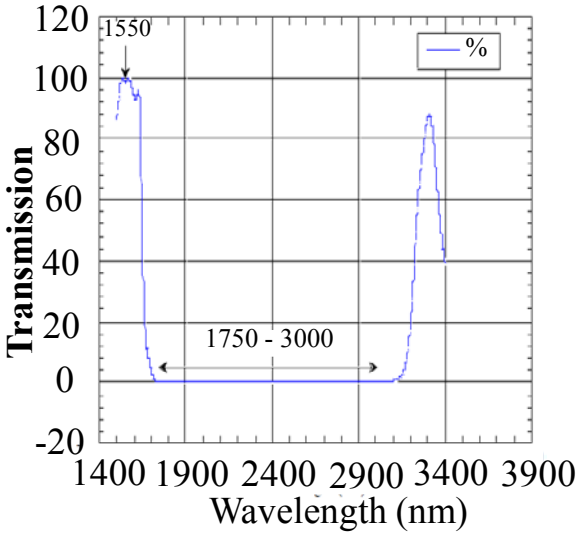
E: Dielectric filter



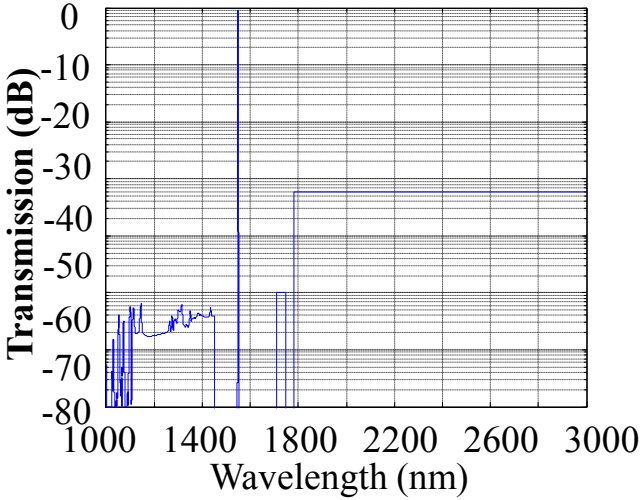
F: 3 nm band-pass filter



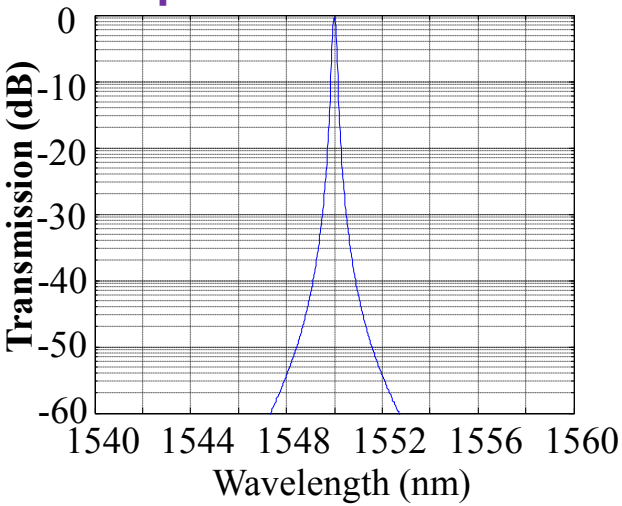
G: Long wave blocking filter



Option 3: E+F+G

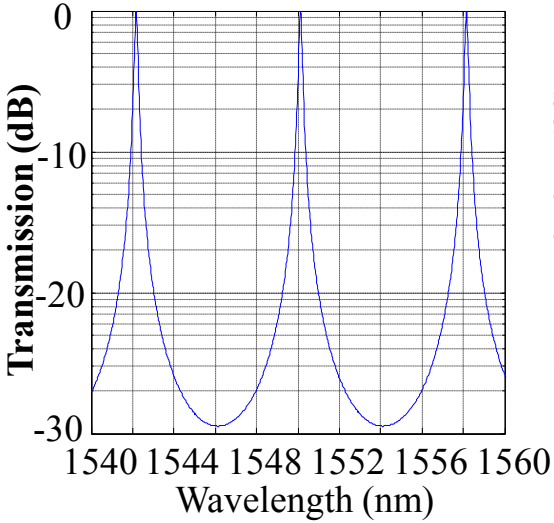


Expanded on the left

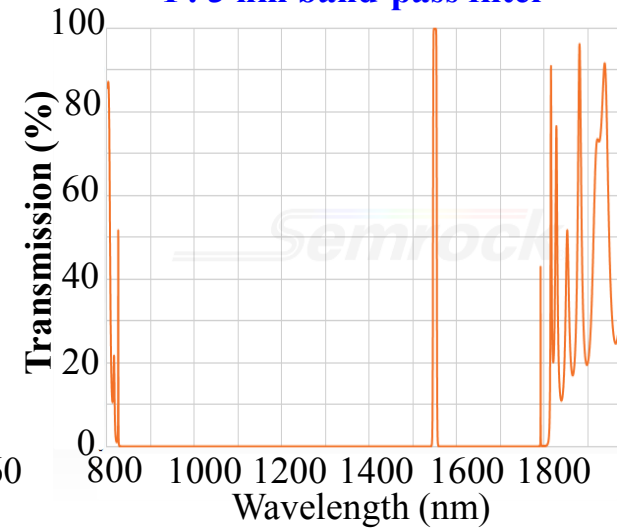


OPTION 4

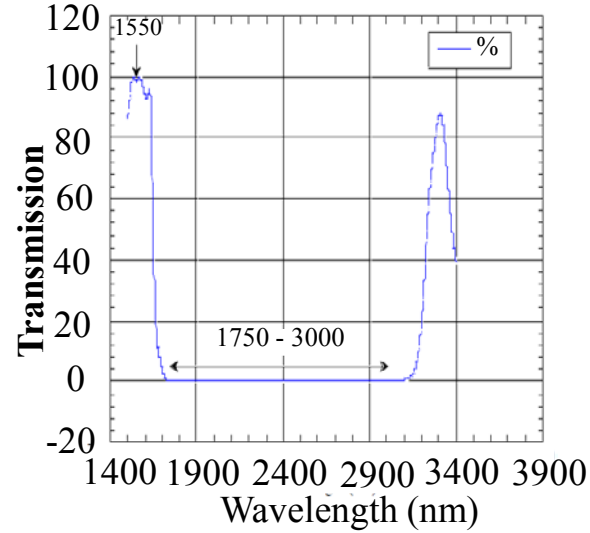
C: FP Etalon



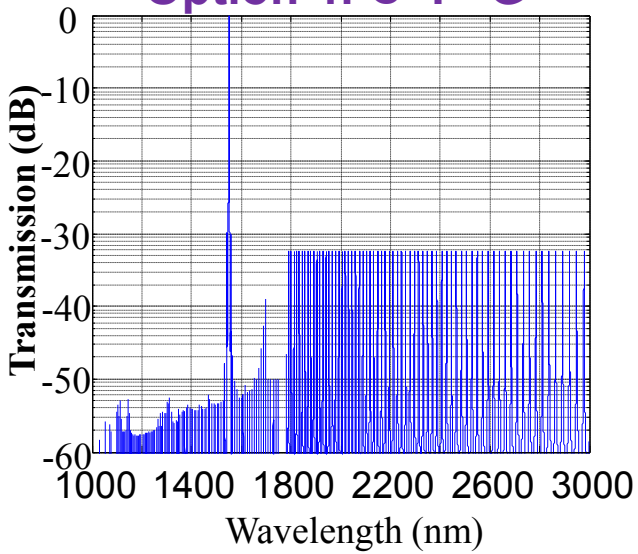
F: 3 nm band-pass filter



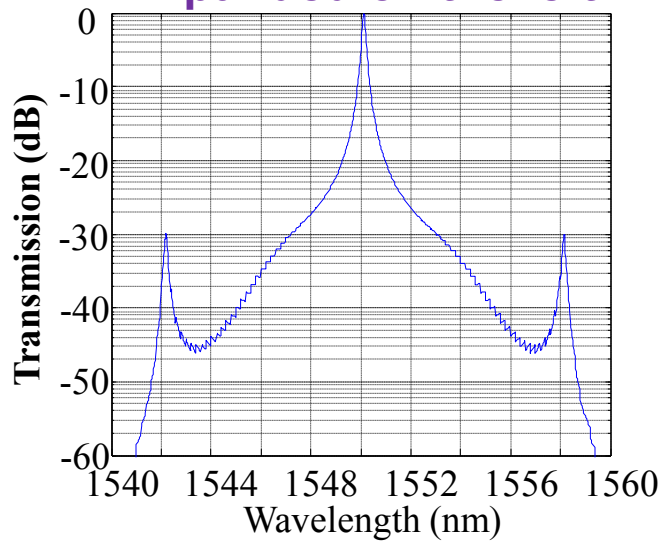
G: Long wave blocking filter



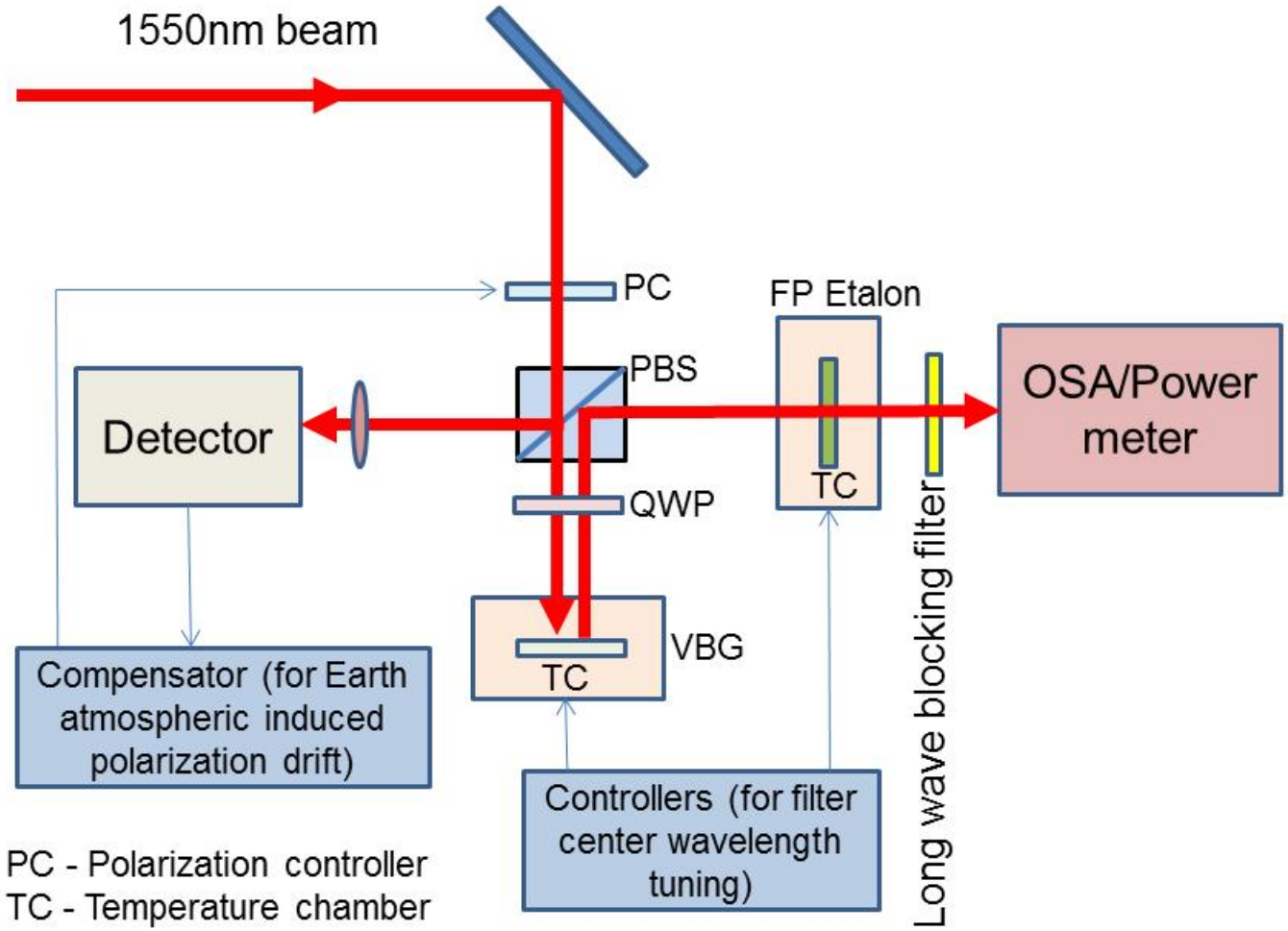
Option 4: C+F+G



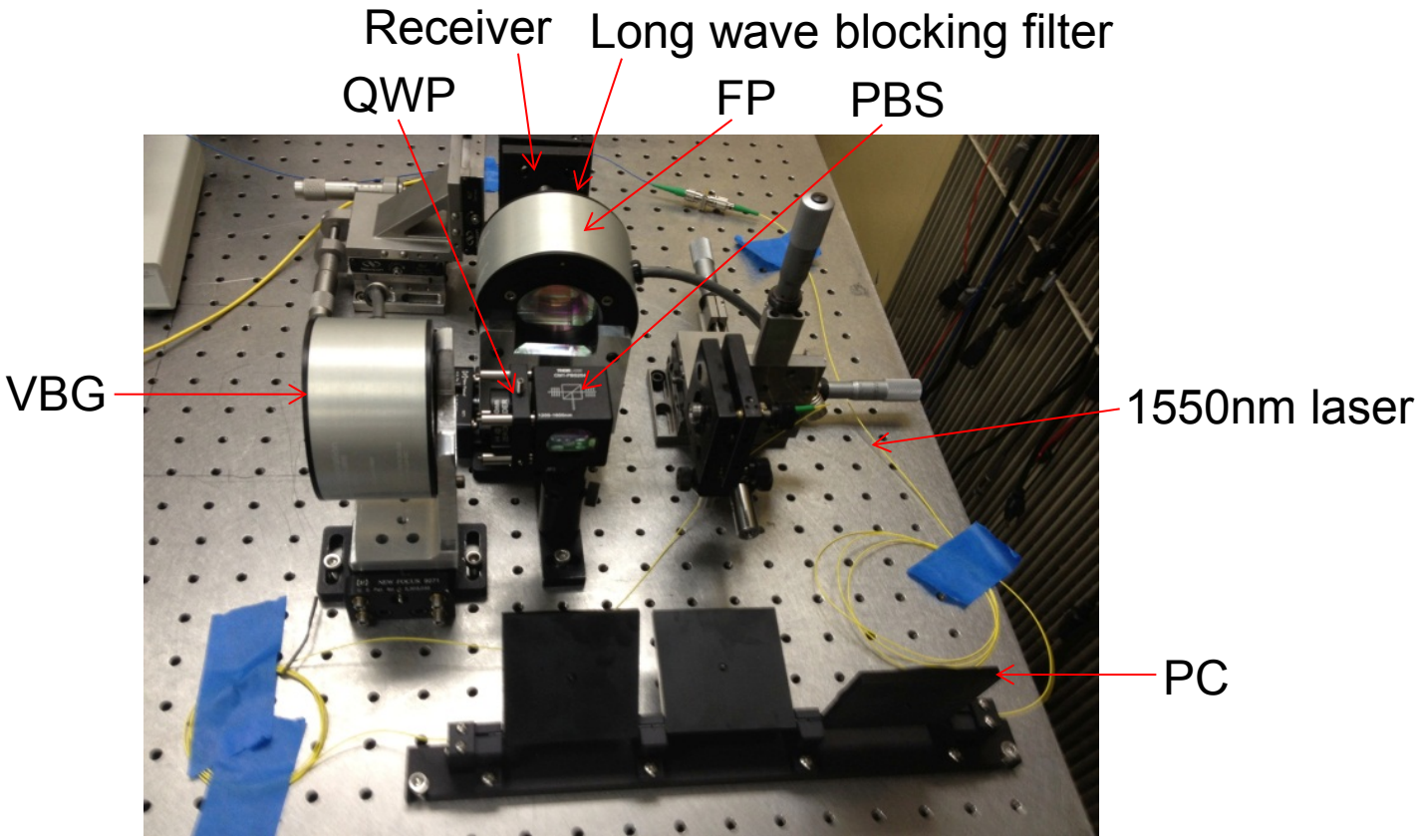
Expanded on the left



LABORATORY EXPERIMENT CONFIGURATION



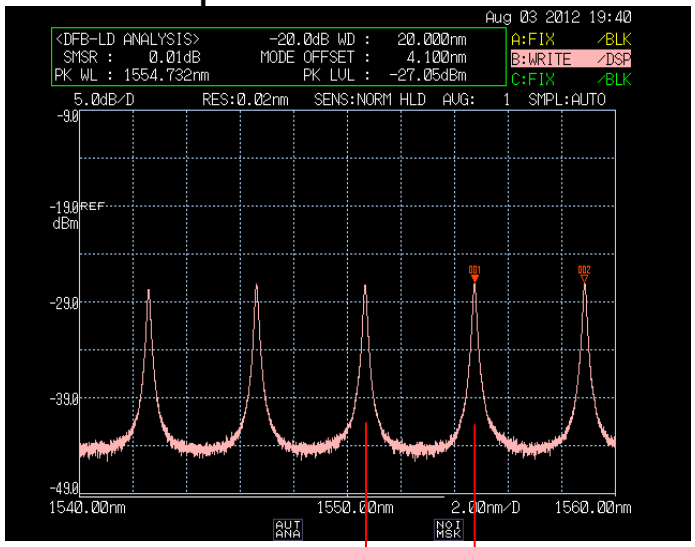
LABORATORY EXPERIMENT SETUP



FABRY-PEROT ETALON TEST

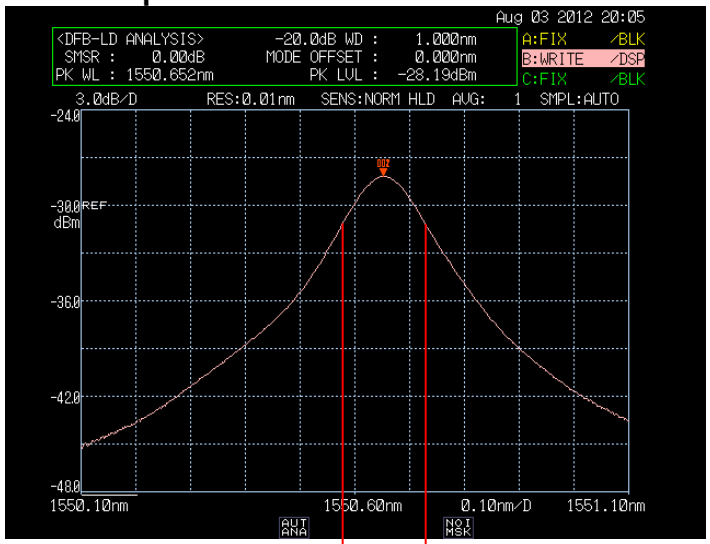
Jet Propulsion Laboratory
California Institute of Technology

Spectrum of FP



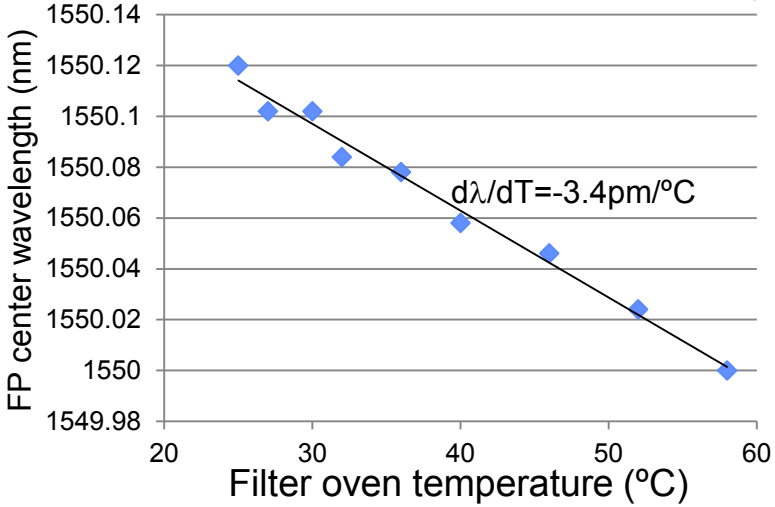
Free spectrum range → 4nm ←

Expanded scale of the left



150pm ↔

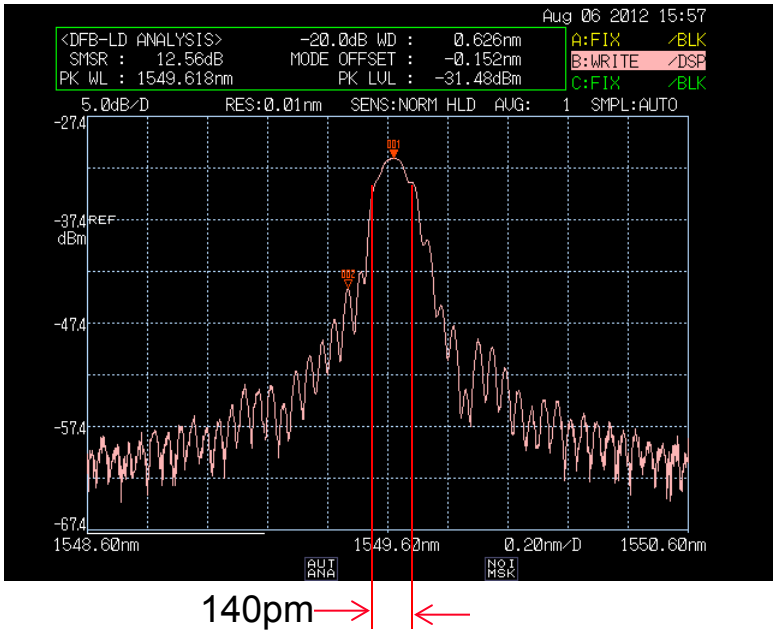
Measured FP temperature tunability



- **Band width =150pm**
- **Transmission efficiency=94%**
- Free spectrum range = 4nm
- Temperature coefficient of $|d\lambda/dT|$=3.4pm/ºC is small because FP is made of ULE
- Required $|d\lambda/dT|>10$, achievable by using fused silica or other material

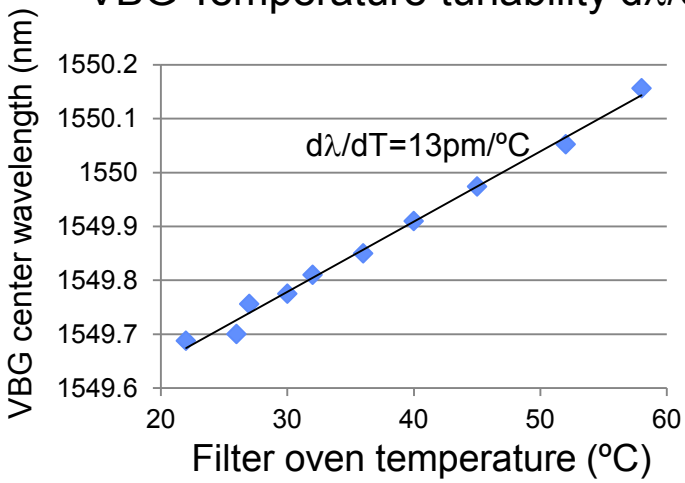
VBG TEST

Measured spectrum of VBG



140pm

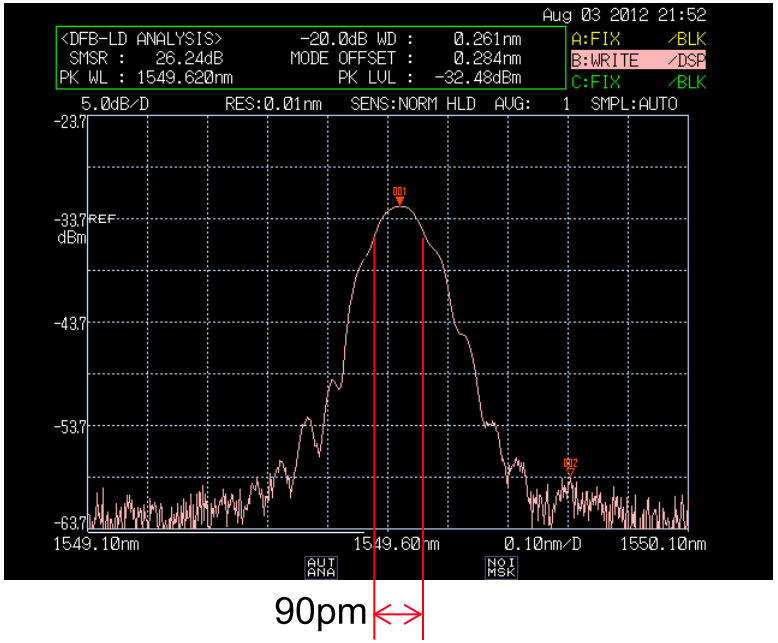
VBG Temperature tunability dλ/dT

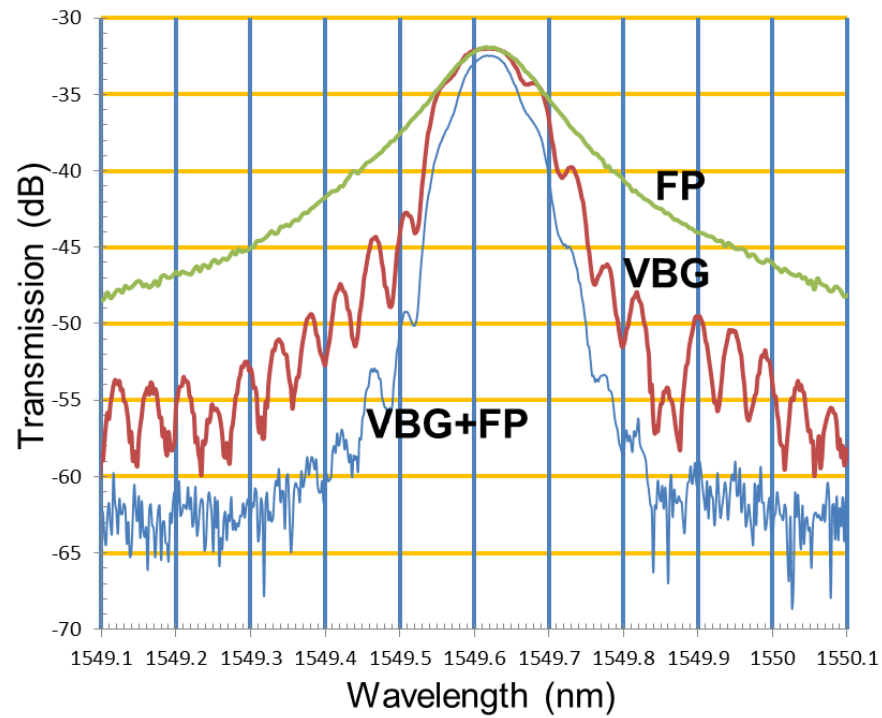


- **Band width =140pm**
- **Transmission efficiency=94%**
- Measured temperature coefficient dλdT=13pm/ºC meets our requirement
- Requiring T>50º to get the center wavelength at 1550.12nm

VBG + FP

Measured spectrum of VBG+FP





- **Band width (FWHM) =90pm**
- **Transmission efficiency=88.4%**

SUMMARY AND FUTURE WORK

- We demonstrated spectral filter assembly with a band-pass of 90 pm over a large 2000 nm operational range at telecommunication window of 1550 nm for DOT ground terminal
- Future work:
  - Design and fabrication of FP with material having large thermal coefficient
  - Design and fabrication of VBG with center wavelength of 1550.12 nm at temperature around 45°C
  - Automatic temperature tunings of FP and VBG filter center wavelengths for tracking the downlink signal wavelength
  - Automation of PC for polarization compensation
  - Custom filter ovens for automation of wavelength tuning and lifting temperature tunable range from current 60°C to 80°C
  - Exploration of Option 2 for implementation with better out-band rejection ratio and transmission efficiency