Downstream 10G wavelength plan and its impact on the ONU triplexer design

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Motivation

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- **1G/10G EPON will require new triplexer design for 1/10 Gbit/s capable ONUs**
- **Examine the impact of 10 Gbit/s downstream wavelength selection on the triplexer design and TFF filter complexity**
- **Assume single triplexer block for 1/10 Gbit/s capable ONUs to be complaint with future IEEE 802.3av**
  - one triplexer design to be used for 1 Gbit/s and 10 Gbit/s transmission
  - if 1 Gbit/s channel is not used, the PD port and connection is not occupied – lower triplexer cost for mass production
  - WDM filters must isolate 1 Gbit/s channel from other channels
- Assure compliance with video overlay delivery in 1550 nm window
- Assure compliance with OTDR service in the 1625+ nm window

Thin Film Filter (TFF) Theory [1]

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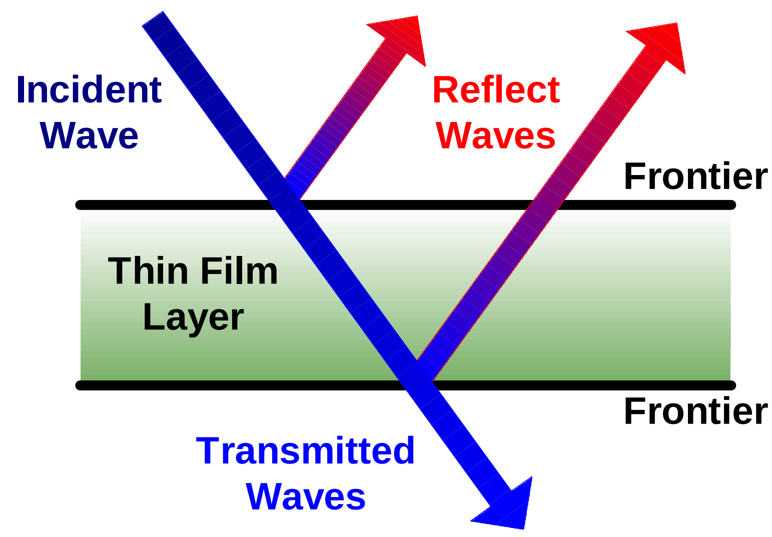
Principle:

- Thin transparent films (TFFs) with various refraction indices are deposited on a glass / metal substract
- Part of the incident waves are reflected on the frontiers of materials with different refractive indices and the other part is transmitted through the layer stack
- The use of non-metallic, or dielectric, coated thin films minimizes the absorption (loss)

Applications:

- Optical Filters
- Anti-reflection Coatings
- Mirrors



Thin Film Filter Theory [2]
Short introduction

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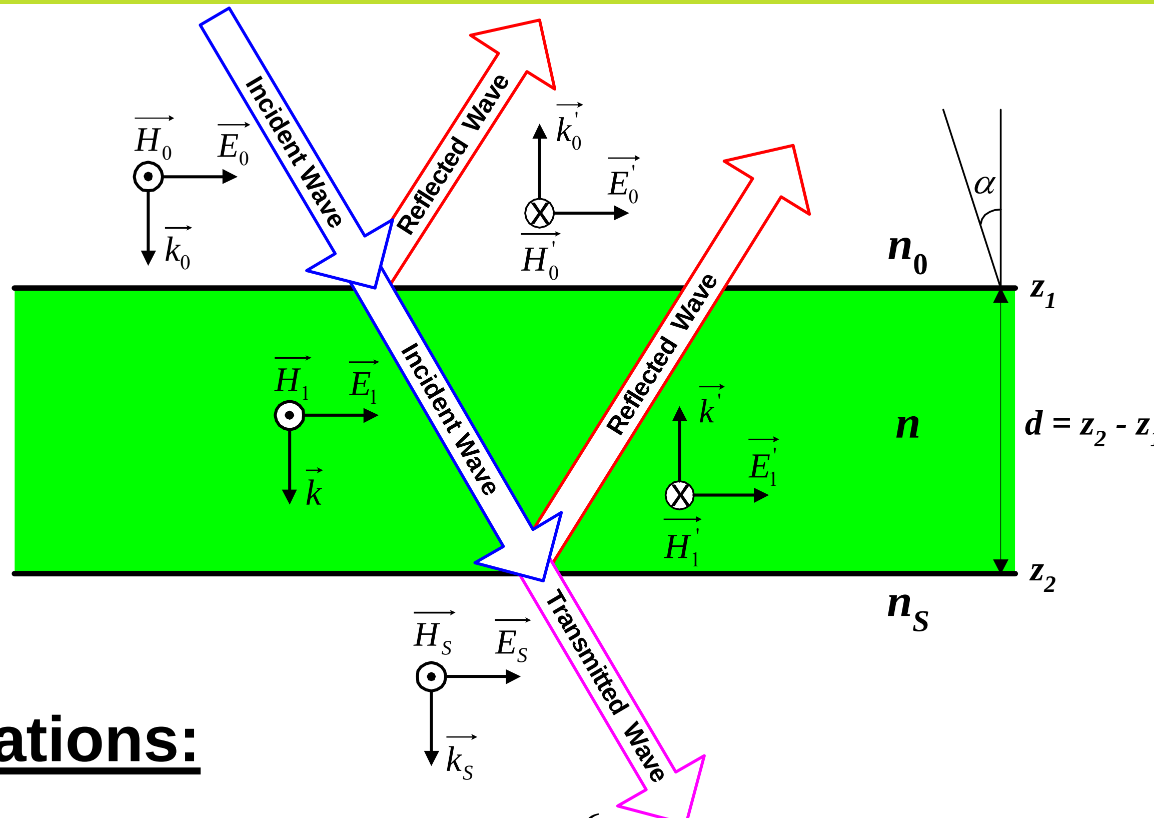

Phase introduced by the material

$$\delta = \frac{2\pi}{\lambda}(nd\cos\alpha)$$

From Maxwell's equations:

1st Material Frontier (Interface z_1)

$$\begin{cases} E_0 + E_0' = E_1 + E_1' \\ H_0 - H_0' = H_1 - H_1' \\ n_0 E_0 - n_0 E_0' = nE_1 - nE_1' \end{cases}$$

2nd Material Frontier (Interface z_2)

$$\begin{cases} E_1 e^{i\delta} + E_1' e^{-i\delta} = E_S \\ H_1 e^{i\delta} - H_1' e^{-i\delta} = H_S \\ nE_1 e^{i\delta} - nE_1' e^{-i\delta} = n_S E_S \end{cases}$$

Thin Film Filter Theory [3]
Basic characteristics of TFFs

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Transmittance and Reflectance Definition:

$$\vec{R} = \frac{E_0'}{E_0} \qquad \vec{T} = \frac{E_S}{E_0}$$

Expressions obtained:

$$\Rightarrow \begin{cases} 1 + \dfrac{E_0'}{E_0} = \left(\cos\delta - i\dfrac{n_S}{n}\sin\delta\right)\dfrac{E_S}{E_0} \\ n_0 - n_0\dfrac{E_0'}{E_0} = \left(-in\sin\delta + n_S\cos\delta\right)\dfrac{E_S}{E_0} \end{cases} \Rightarrow \begin{pmatrix} 1 \\ n_0 \end{pmatrix} + \begin{pmatrix} 1 \\ -n_0 \end{pmatrix}\vec{R} = M\begin{pmatrix} 1 \\ n_S \end{pmatrix}\vec{T}$$

<u>Single Layer Transfer Matrix:</u>

$$M = \begin{pmatrix} \cos\delta & -\dfrac{i}{n}\sin\delta \\ -in\sin\delta & \cos\delta \end{pmatrix} = \begin{pmatrix} M_{11} & iM_{12} \\ iM_{21} & M_{22} \end{pmatrix}$$

Thin Film Filter Theory [4]
T/R amplitude and phase

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Transmittance and Reflectance Amplitude:

$$\vec{R} = \frac{n_0 M_{11} + i n_0 n_S M_{12} - i M_{21} - n_S M_{22}}{n_0 M_{11} + i n_0 n_S M_{12} + i M_{21} + n_S M_{22}}$$

$$\vec{T} = 1 - \vec{R} = \frac{4 n_0 n_S}{n_0 M_{11} + i n_0 n_S M_{12} + i M_{21} + n_S M_{22}}$$

Transmittance and Reflectance Intensity and Phase:

$$R = \vec{R}\vec{R}^*$$

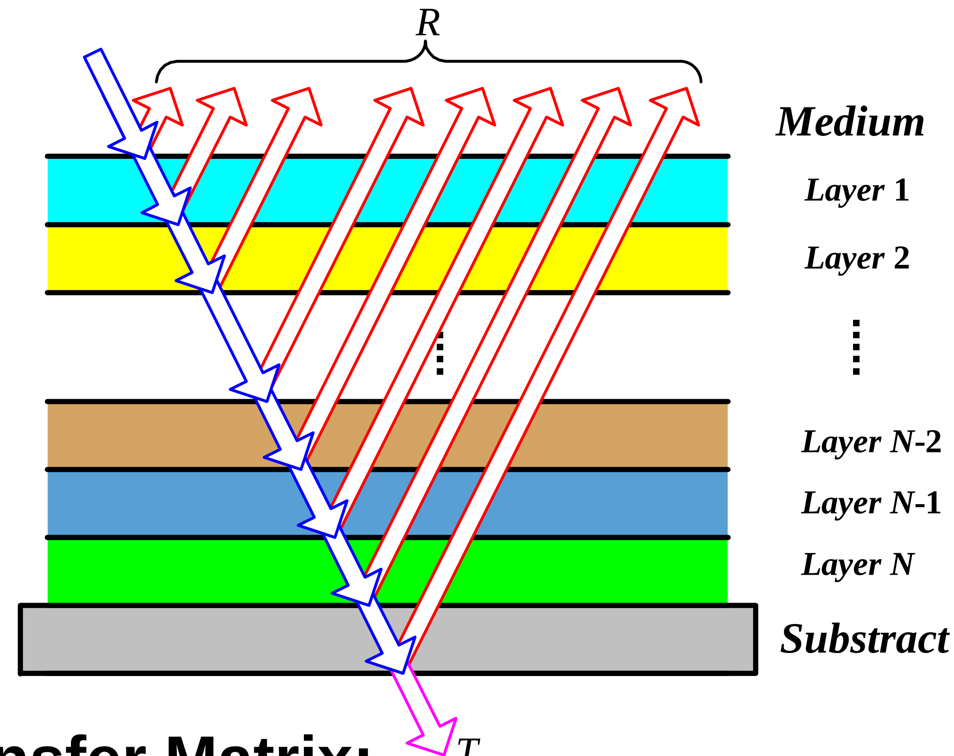
$$T = \frac{n_S}{n_0} \vec{T}\vec{T}^*$$

$$\sigma_R = \arg\left(\vec{R}\right)$$

$$\sigma_T = \arg\left(\vec{T}\right)$$

Thin Film Filter Theory [5]
TFF stacks

Multi-layer Thin Film Filter:



Equivalent Transfer Matrix:

$$M_T = M_1 \times M_2 \times \ldots . \times M_N = \begin{pmatrix} M_{11} & iM_{12} \\ iM_{21} & M_{22} \end{pmatrix}$$

TFF Implementation [1]

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Typical Thin Film Filter construction:

- **Incident medium of air or optical cement**
- **Several layers (can easily exceed 200 layers, depending on the target spectral characteristic)**
- **Different materials (limited to 2 or 3 types)**
- **Different layer thickness (between [0.5, 2]*QWOT)**
  - QWOT = Quarter Wavelength Optical Thickness
- **Different incident wave angle (between [0º, 90º])**

$$n_x \lambda = \lambda_0 \quad \Rightarrow \quad d_x = \frac{\lambda_x}{4} = \frac{\lambda_0}{4 n_x}$$

TFF Implementation [2]

Typical TFF materials:

Material	Refractive Index	Wavelength Range (nm)
Si	3.42	1 - 8
ZnS	2.3	0.4 - 14
SiO	1.85	1 - 8
Al_2O_3	1.6	1 - 9
Si_2O_3	1.55	0.3 - 8
SiO_2	1.45	0.16 - 8

Triplexer architecture

TFF filter design process

Triplexer Architecture [1]

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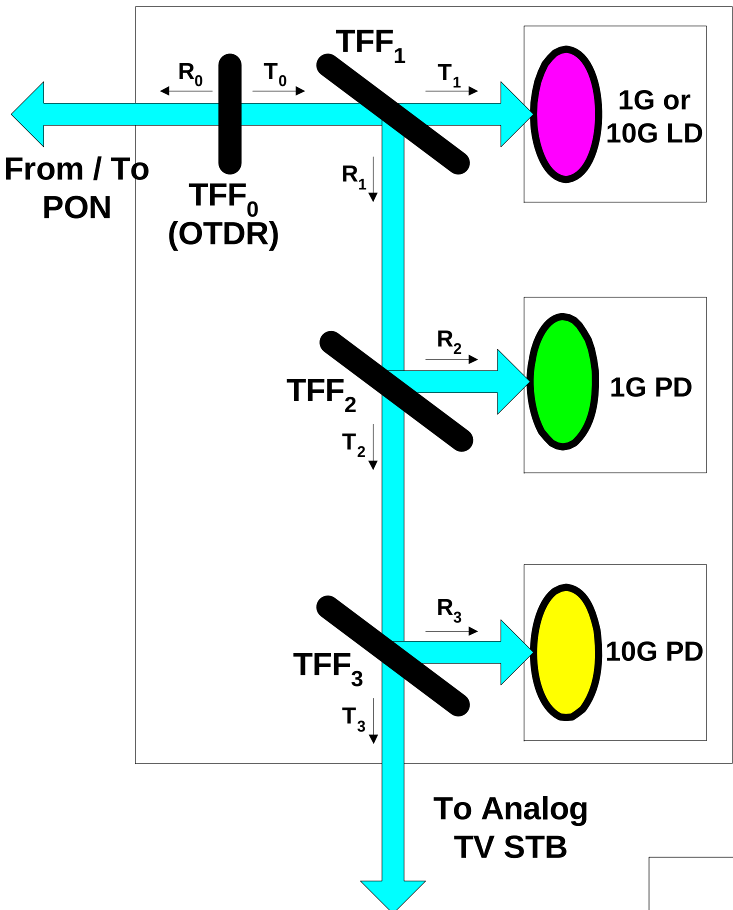
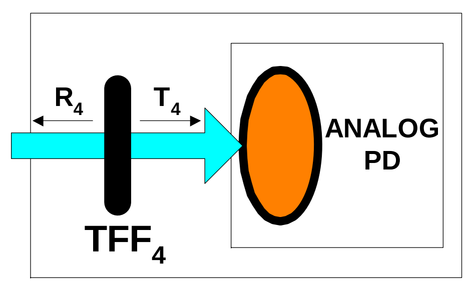


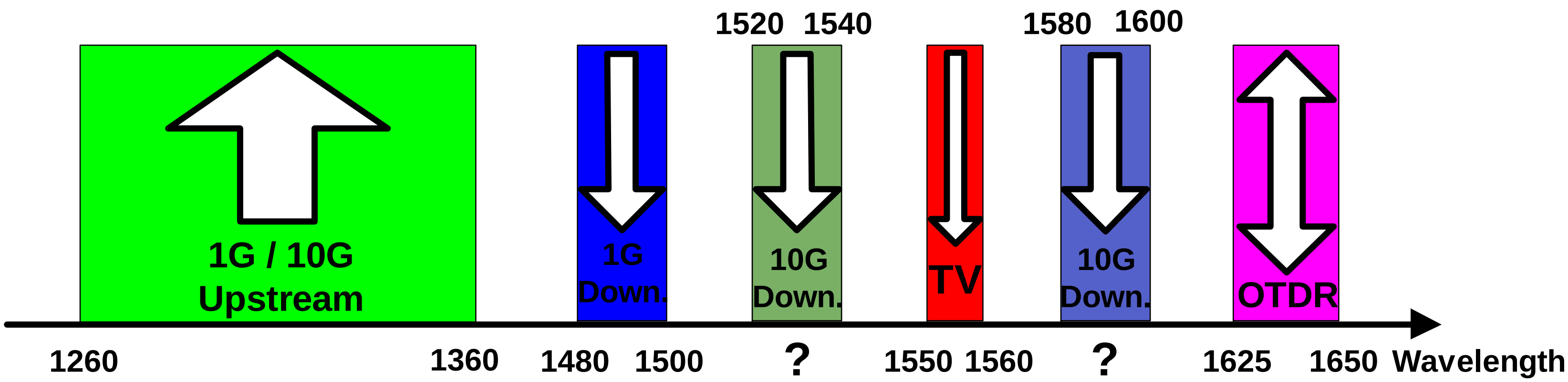


Targets:

- Minimize additional channel loss for 1 Gbit/s channel
- Compact, simple and robust construction
- Minimization of the number of applied TFF filters

Triplexer Architecture [2]
Wavelength allocation options

Filtering Characteristics:



- High channel isolation (low crosstalk)
- Low passband and insertion losses
- Simple filter configuration (minimum number of layers)

Triplexer Architecture [2]
TFF filtering options

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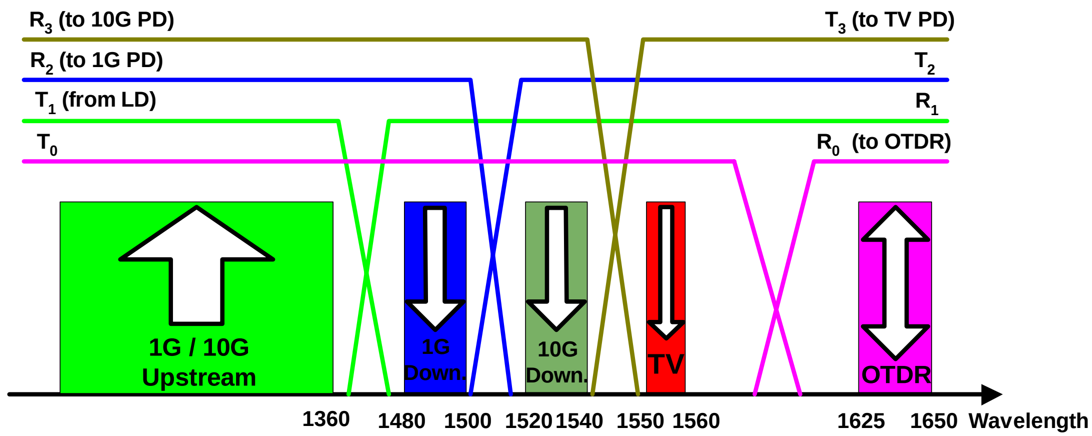
10G Downstream at [1520,1540] nm (Option 1)



- TFF_0 separates the OTDR signal from all the others
- TFF_1 transmits the upstream data signal coming from the LD and reflects all the downstream channels
- TFF_2 reflects the 1G data downstream signal to the respective PD
- TFF_3 reflects the 10G data downstream signal to the PD and transmits the analog TV overlay channel
- There is no need to use TFF_4 because TV signal is already isolated
- TFF_2 and TFF_3 need to have a steep cut-off response

Triplexer Architecture [3]
TFF filtering options

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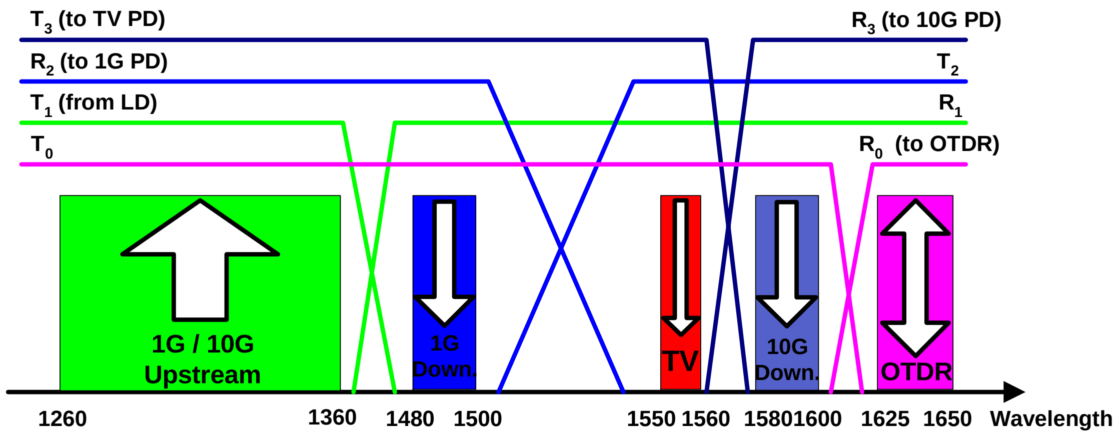
10G Downstream at [1580,1600] nm (Option 2)



- TFF_0 reflects the OTDR signal and transmits all the others
- TFF_1 transmits the upstream data signal and reflects the others
- TFF_2 reflects the 1G data downstream signal to the PD
- TFF_3 reflects the 10G data downstream signal to the PD and transmits the analog TV overlay channel to the PD
- No need for TFF_4 because TV signal is already isolated
- TFF_0 and TFF_3 need to have a steep cut-off response to provide good channel isolation/separation

TFF design [1]
Genetic Algorithms

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Reasons to use it:

- Thin Film Filter synthesis is a highly complex task
- Huge solution space (generating all possible solutions or applying a “trial and error” method is not feasible)

Advantages:

- Fast convergence method
- Benefit from crossing the best solutions

Disadvantages:

- Convergence process is not guaranteed
- Final solution may not be global (may get stuck in local minimum)

TFF design [2]
Genetic Algorithms

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Initial Population Generation:

- Create M filters with random number of layers limited by an initial maximum size (e.g., 20 layers)
- Randomly choose the material of each QWOT layer (consecutive layers may repeat the same material)
- Obtain the cost of each obtained filter through the evaluation made by the Cost Function

Examples of initial filters:

- Filter #1 **HLHLHLHLHLHLHLHLHLHL** $= (HL)^{10}$
- Filter #2 **HHLHLHH** $= H(HL)^2H^2$

⋮ ⋮ ⋮

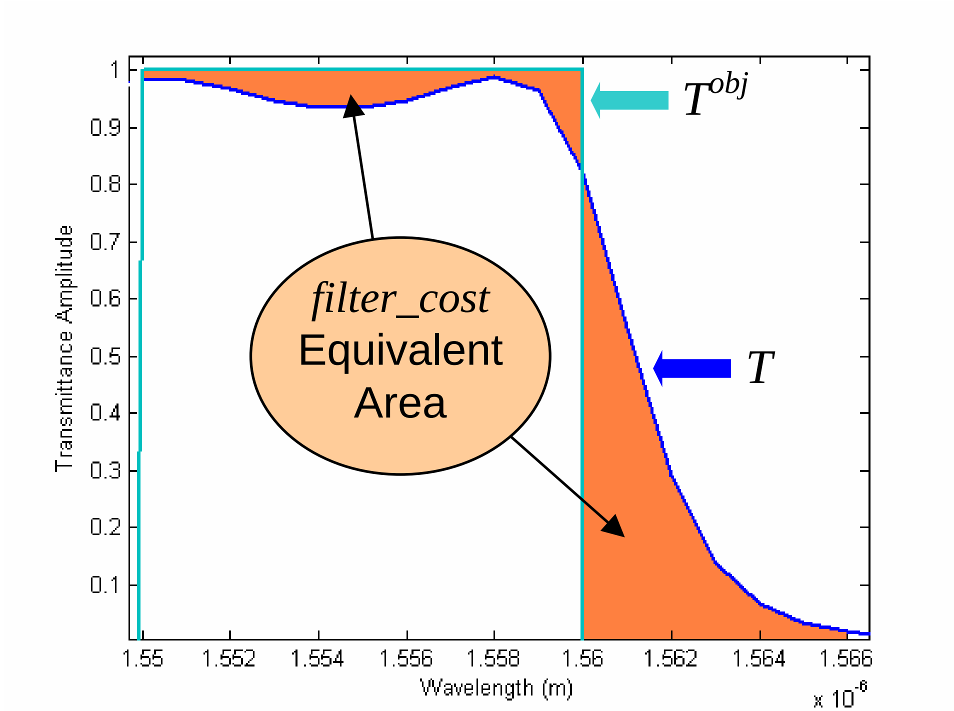
- Filter #M **LLLHLLHHLHLLLLHHL** $= L^3HL^2H^2LHL^4H^2L$

TFF design [3]
Genetic Algorithms

Filter Cost Function

Calculates the difference between the spectral response of the transmittance T or reflectance R and the objective response T^{obj} or R^{obj}, respectively, of a given TFF *filter*:

$$filter\_cost \left\langle \begin{array}{l} \displaystyle\sum_{\lambda \in \left\{T^{obj}\right\}} \left| T_{\lambda}^{obj} - T_{\lambda} \right| \\ \displaystyle\sum_{\lambda \in \left\{R^{obj}\right\}} \left| R_{\lambda}^{obj} - R_{\lambda} \right| \end{array} \right.$$



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Selection of the best filters:

- The best *N* filters are picked and ordered by the lower cost values (calculated using cost function)
- Objective function of the Genetic Algorithm:

$$Minimize\,(filter\_cost)$$

- All the other *M*-*N* filters are excluded for further optimization process

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Mutation:

•If the number of identical filters is greater than a given fraction (e.g., 20 %) of the N best filters, the mutation is applied

•The mutation process changes the refraction index of randomly selected filter layers

•The quantity of changed layers is limited by a fraction of the filter total size (e.g., 60 %)

Example:

- Before Mutation **HLHLHLHLHL = $(HL)^5$**
- After Mutation **LHHHHLLLLH = $L(H)^4(L)^4H$**

Changed layers

TFF design [6]
Genetic Algorithms

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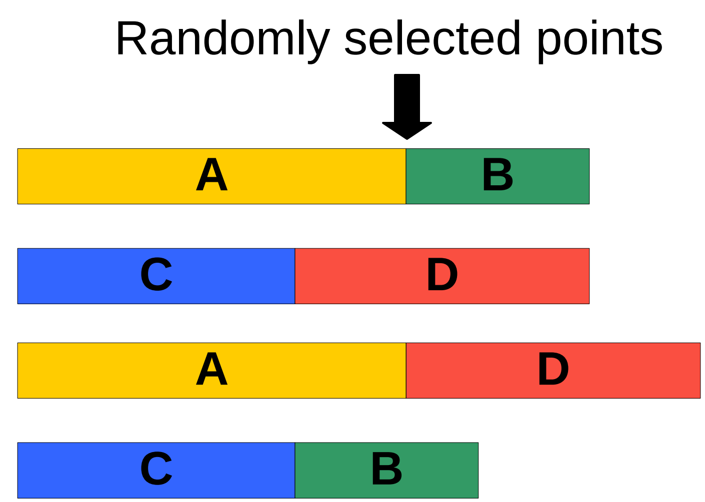
Crossover process:

- The best filters are combined using a random “splice and cut” method
- Filters are selected by pairs (called parents), each one creates two new filters (called children)

Example:

- Parent #1 HLHLHLHL
- Parent #2 HHHHLLLL
- Child #1 HLHLHLLLLLL
- Child #2 HHHHHL



TFF design [7]
Genetic Algorithms

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Population renewal process:

• If, after a number of iterations (e.g., 6) the cost of the N best filters does not change or increases, the filter family is renewed

• Only the best filter is maintained for further optimization

• The new filters size is randomly chosen from the size if the actual best filter

• In this way, a local optimum solution can be avoided

Triplexer architecture

TFF filter design process

Optimization results

Option 1 – TFF_0

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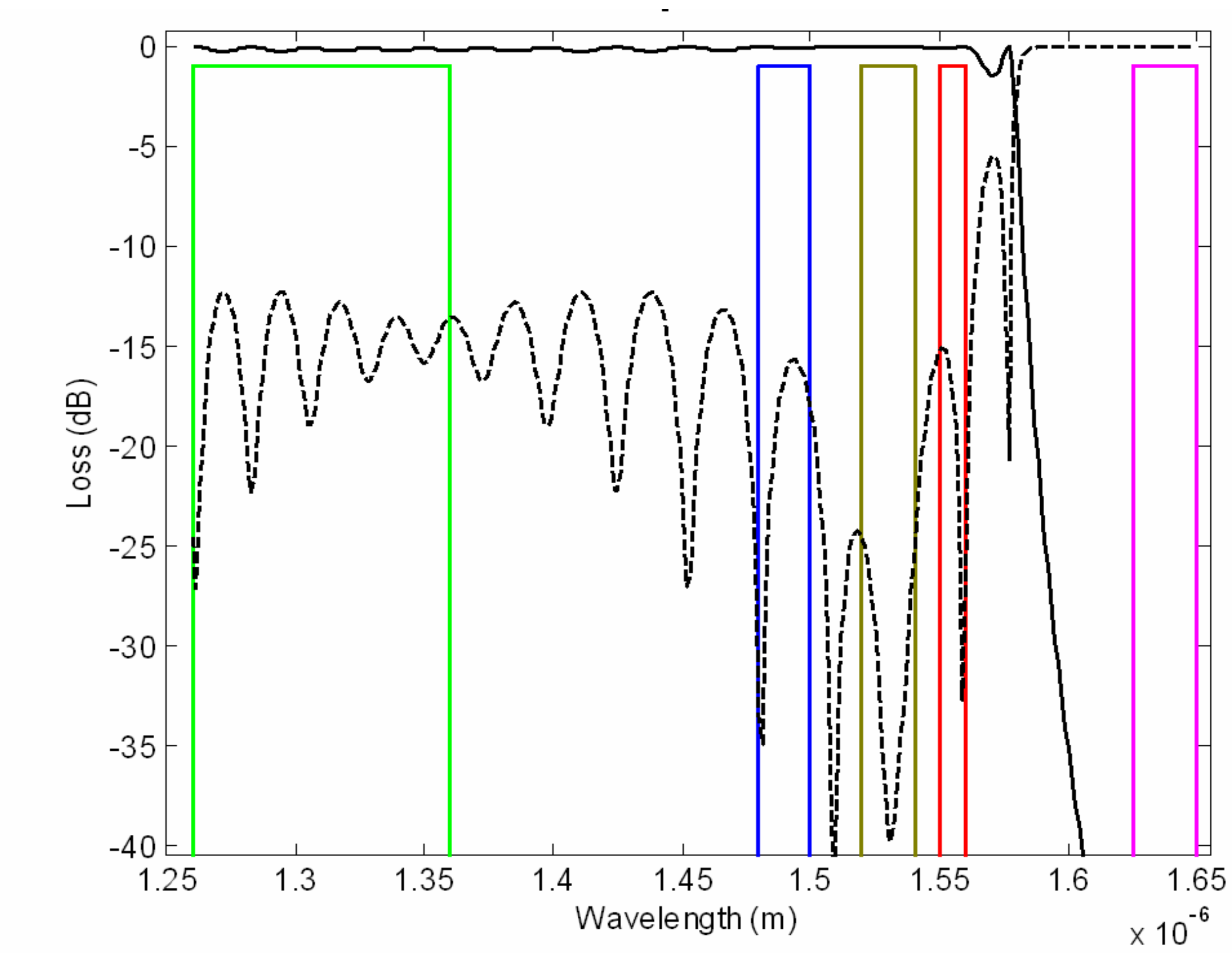

solid curve: **Transmittance**

dashed curve: **Reflectance**

Option 2 – TFF_0

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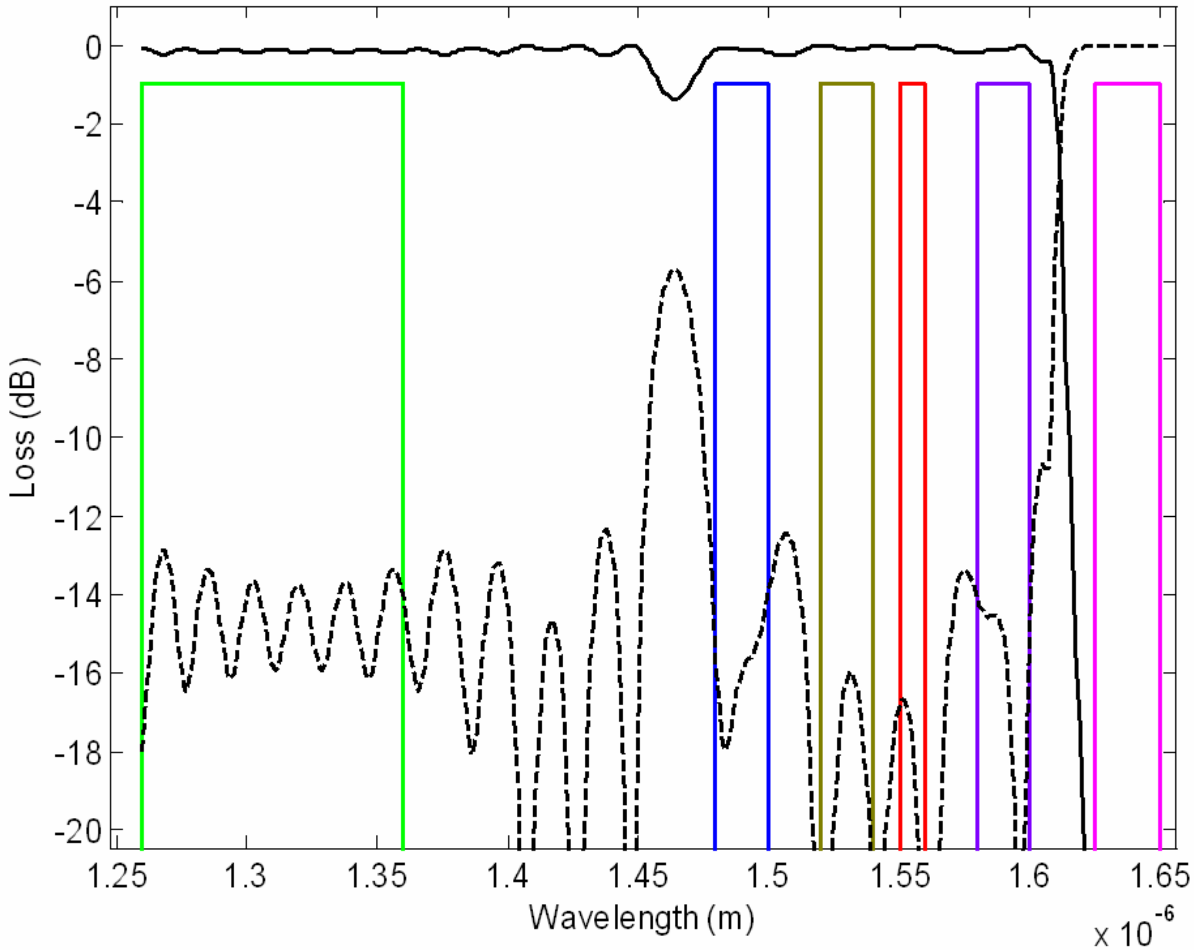

solid curve:
Transmittance

dashed curve:
Reflectance

Option 1/2 – TFF_1

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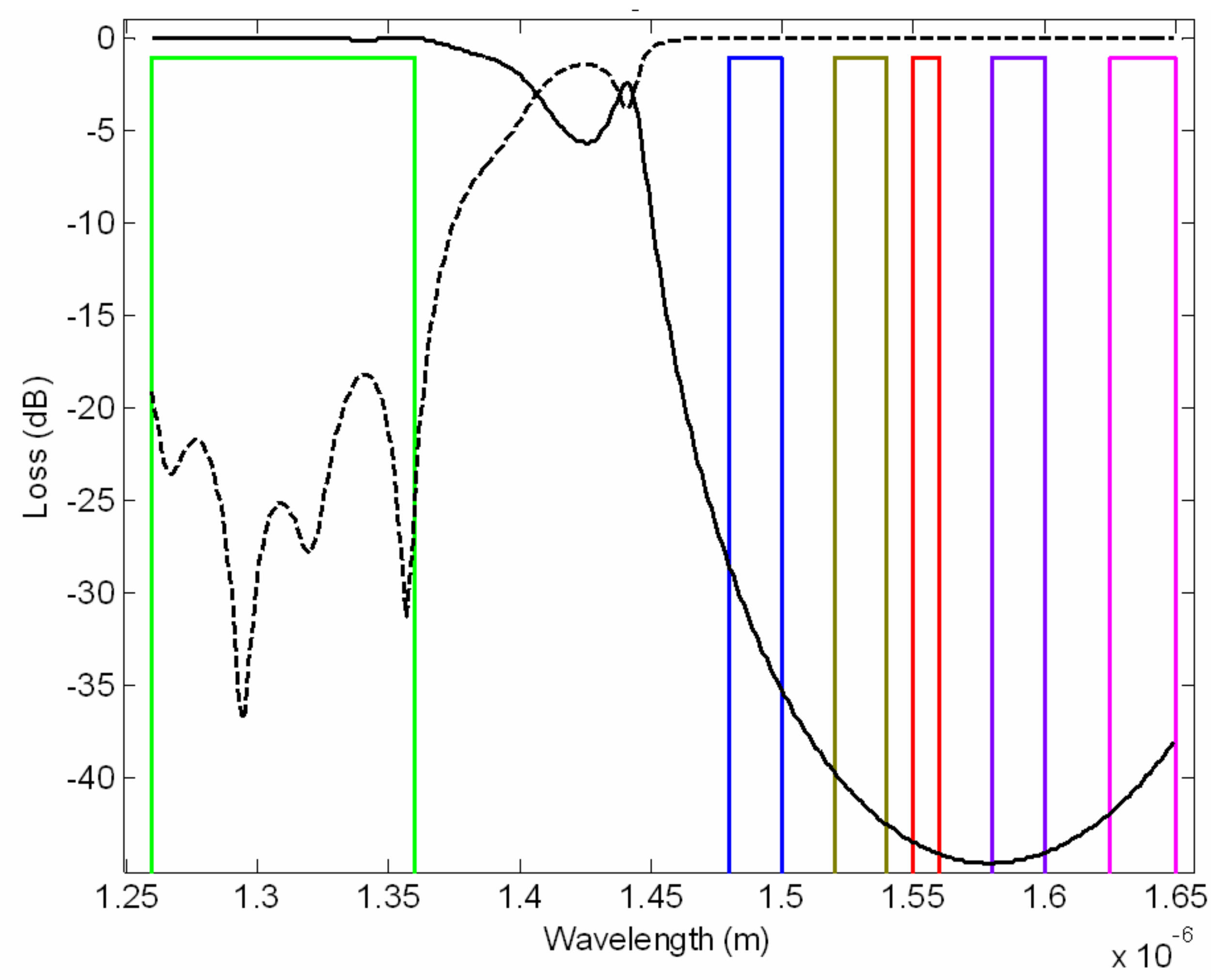

solid curve:
Transmittance

dashed curve:
Reflectance

Option 1 – TFF_2

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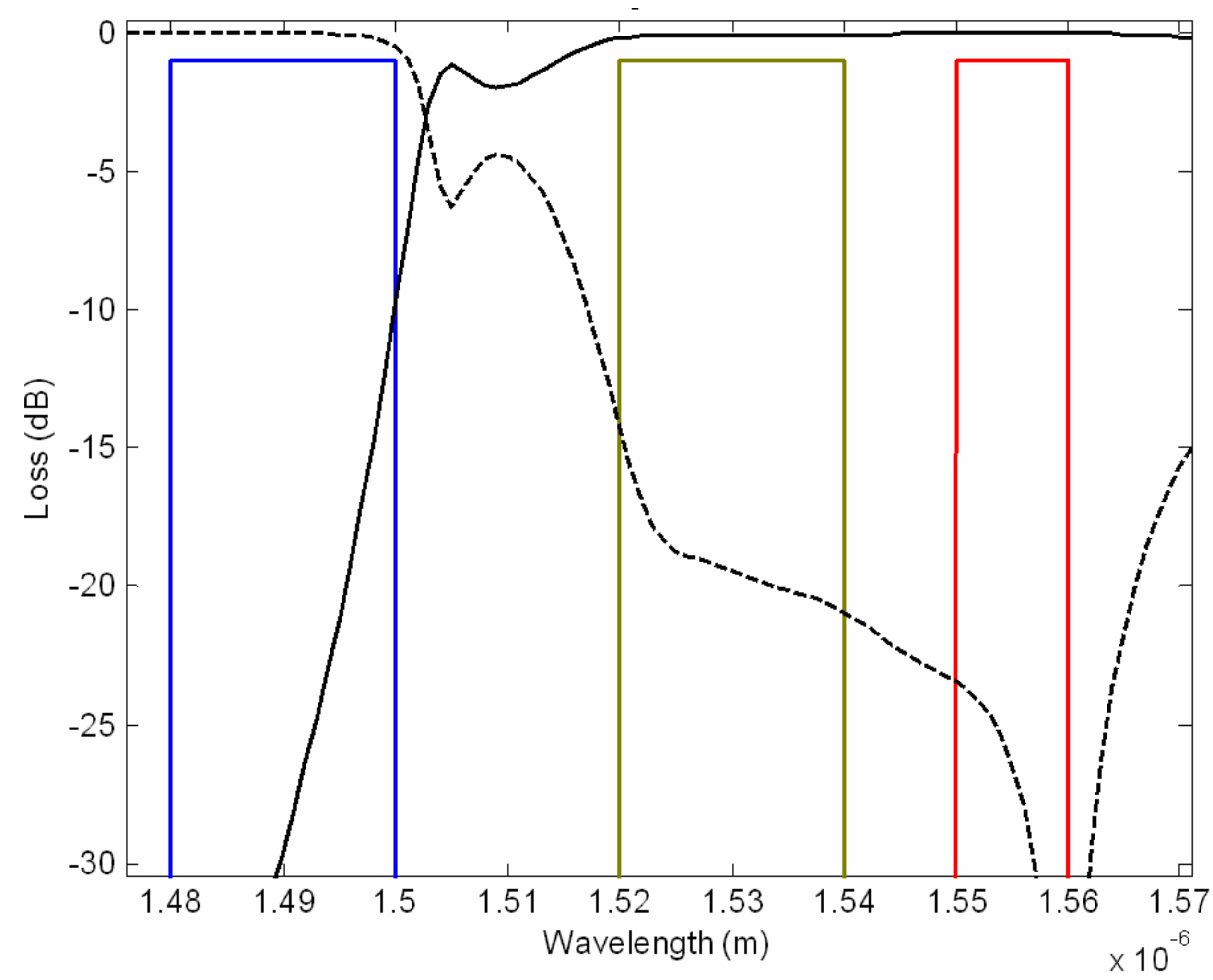

solid curve: **Transmittance**

dashed curve: **Reflectance**

Option 2 – TFF_2

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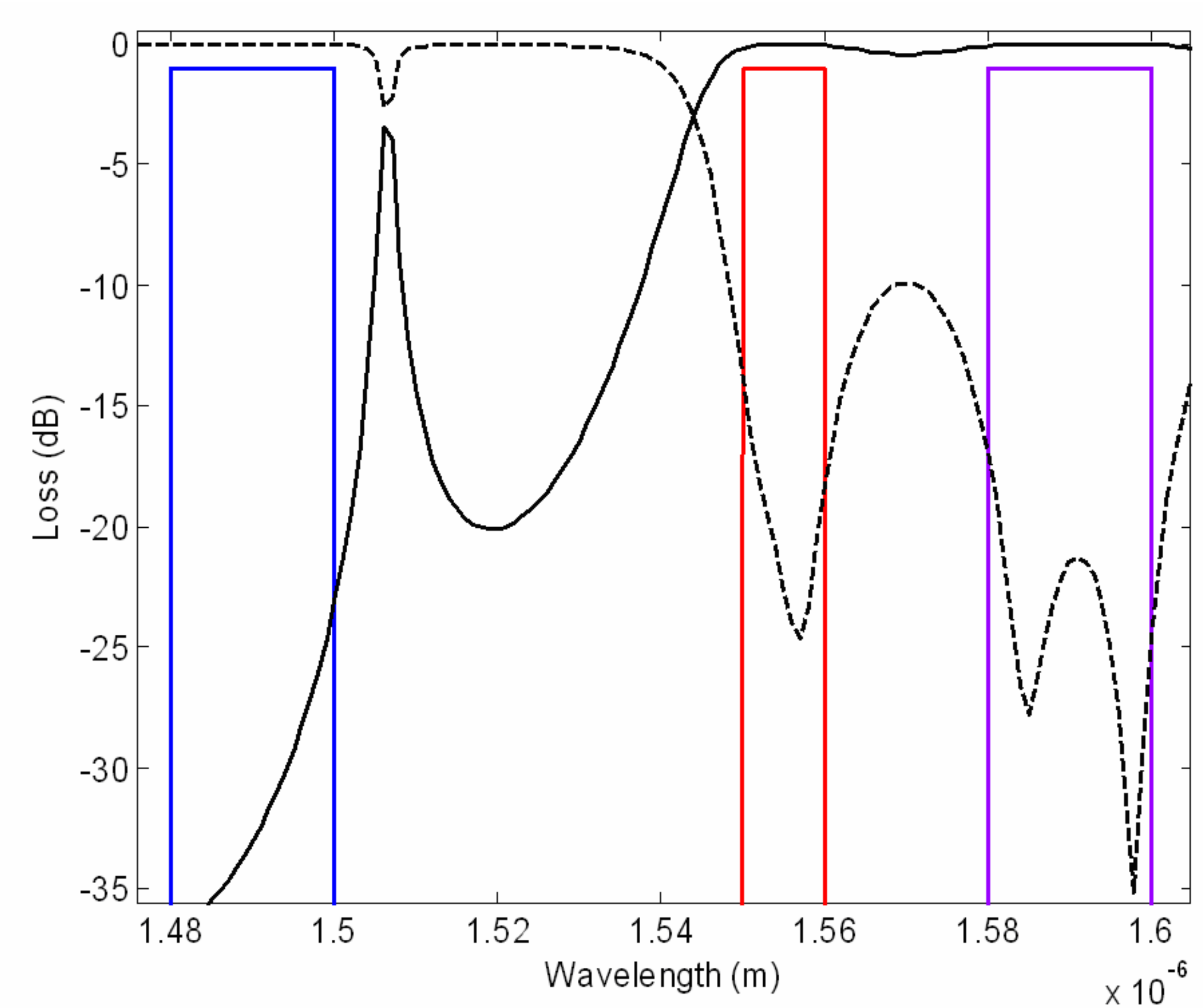

solid curve:
Transmittance

dashed curve:
Reflectance

Option 1 – TFF_3

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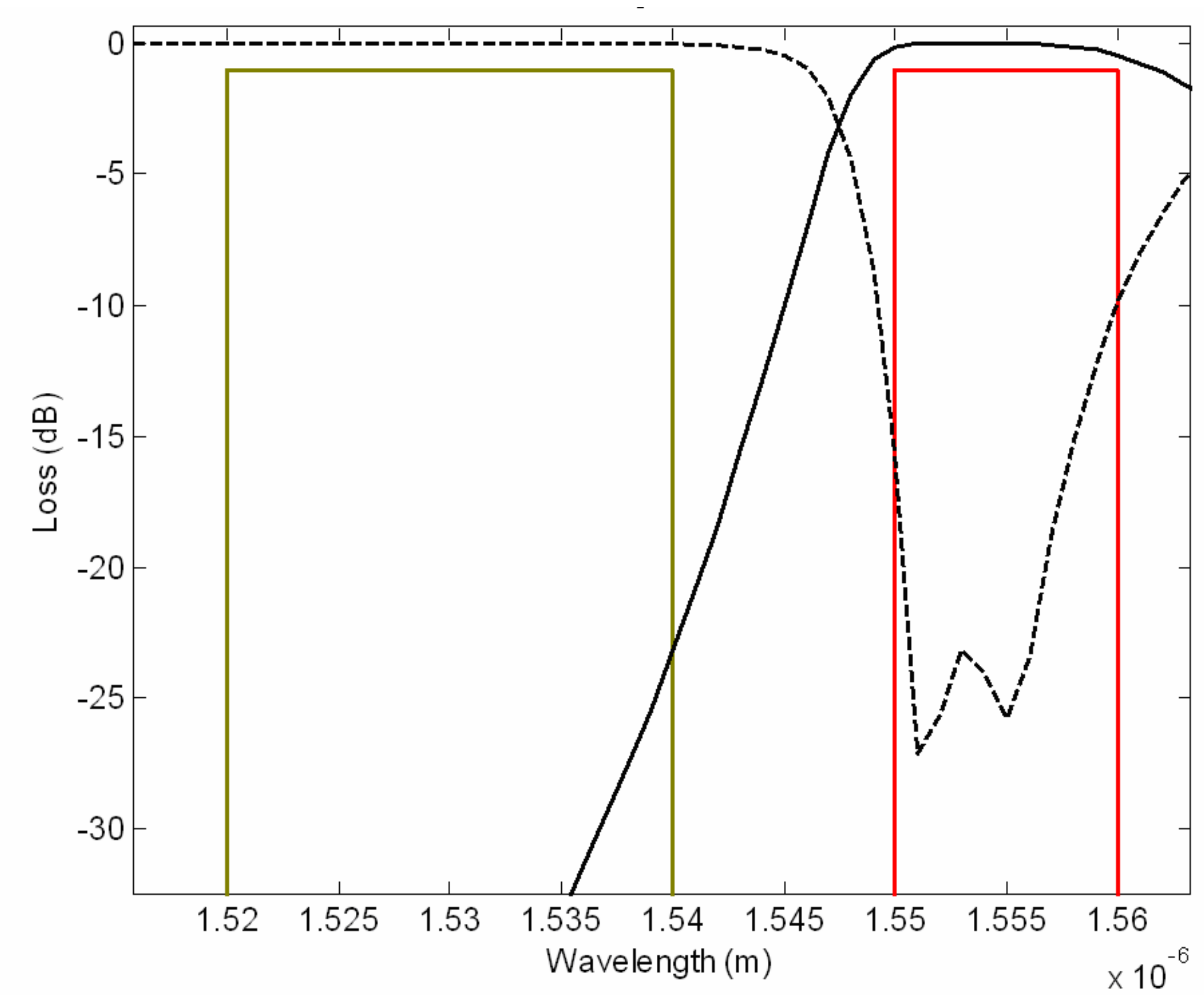

solid curve:
Transmittance

dashed curve:
Reflectance

Option 2 – TFF_3

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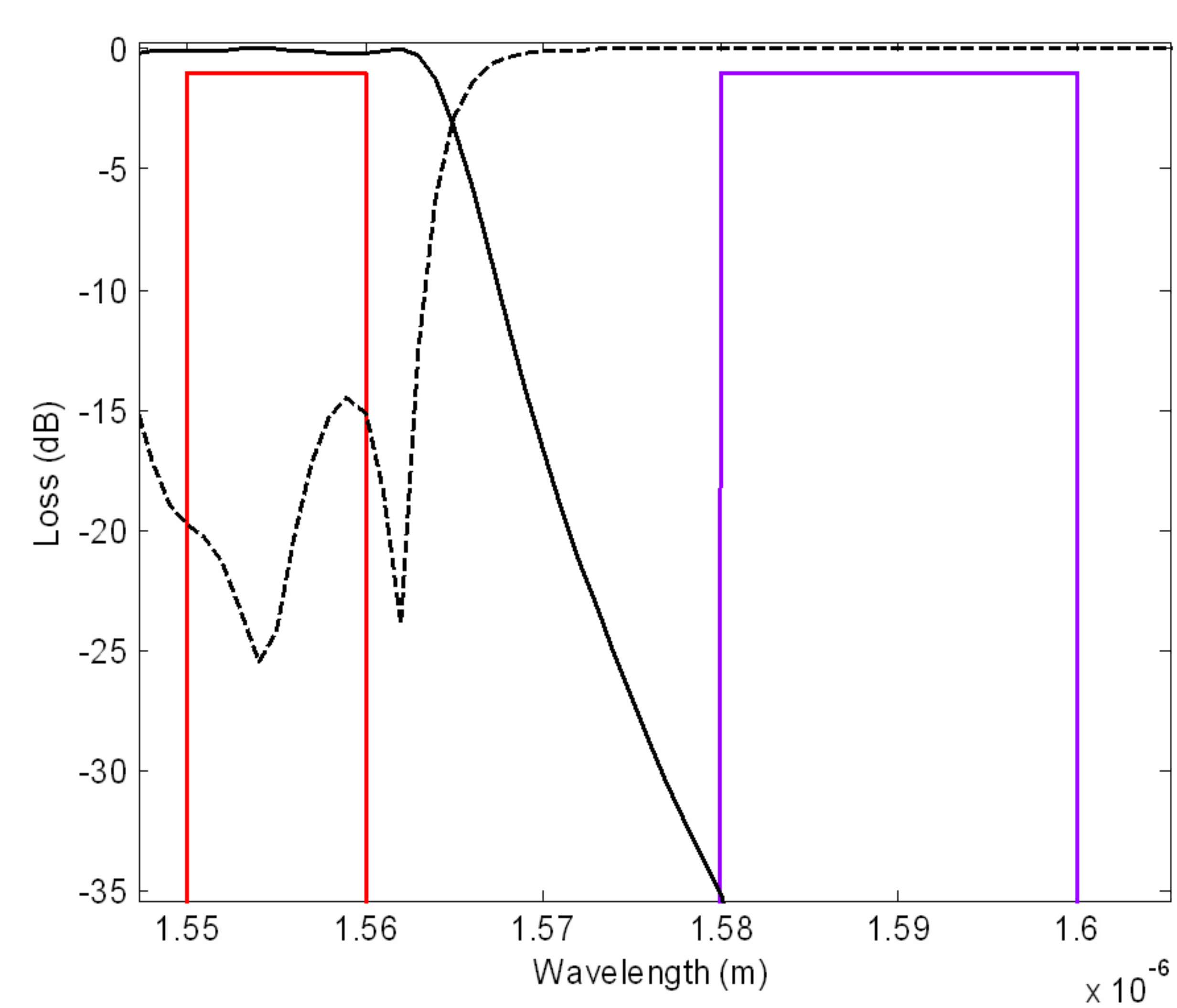

solid curve:
Transmittance

dashed curve:
Reflectance

Filter parameters

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Filter	Option	Layer count	Incident angle θ_0	Central wavelength λ_0
TFF_0	1	103	0º	1350 nm
TFF_0	2	136	0º	1320 nm
TFF_1	1/2	80	45º	1150 nm
TFF_2	1	147	45º	1310 nm
TFF_2	2	154	45º	1350 nm
TFF_3	1	138	45º	1300 nm
TFF_3	2	156	45º	1200 nm

TFF filter loss for individual filters

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T/R	Option	Optical signal loss (dB)					
		1G/10G Up.	1G Down.	10G (1) Down.	Analog Video	10G (2) Down.	OTDR
T_0^*	1	0.12	0.1	0	0.08	-	59
R_0^*	1	-	-	-	-	-	0
T_0^{**}	2	0.12	0.1	0.1	0.08	0.14	40
R_0^{**}	2	-	-	-	-	-	0
T_1	1/2	0.01	32	41	44	44.5	-
R_1	1/2	25	0	0	0	0	-
T_2^*	1	-	30	0.05	0	-	-
R_2^*	1	-	0	20	26	-	-
T_2^{**}	2	-	33	-	0.03	0.03	-
R_2^{**}	2	-	0	-	22.5	21.5	-
T_3^*	1	-	-	41.3	0.01	-	-
R_3^*	1	-	-	0	25.8	-	-
T_3^{**}	2	-	-	-	0.02	47.5	-
R_3^{**}	2	-	-	-	24	0	-

Total loss accounted for each band

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*- option 1, ** - option 2

	Optical signal loss (dB)				
	1G/10G Up.	1G Down.	10G* Down.	Analog Video	10G** Down.
TFF_0*	0.12	0.1	0	0.08	-
TFF_0**	0.12	0.1	0.1	0.08	0.14
TFF_1	0.01	0	0	0	0
TFF_2*	-	0	0.05	0	-
TFF_2**	-	0	-	0.03	0.03
TFF_3*	-	-	0	0.01	-
TFF_3**	-	-	-	0.02	0
Connect.	0.5	0.5	0.5	0.5	0.5
C-lens	0.1	0.1	0.1	0.1	0.1
TOTAL	**0.73**	**0.7**	**0.65* or 0.75****	**0.69* or 0.73****	**0.77**

Conclusions

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• The obtained results indicate that the total power loss in the triplexer module stays always below 1 dB threshold, which together with high channel isolation values, comprises a satisfactory solution for the quadplexer module

• The obtained TFF structures are technically feasible (<200 layers) and can tolerate large production tolerances (up to 15-20% with 1-2% changes in the loss figures)

• Isolation values above 20 dB between channels were always obtained and pass-band loss < 0.15 dB

• In terms of TFF design, Option 1 (10 Gbit/s channel in 1520 – 1540 nm window) seems slightly less stringent for TFF design (fewer layers, loss lower by ~0.1 dB)