6 Technical Feasibility of NG-EPON

6.5 Optical Transmitters

6.5.1 Raman Mitigation in downstream NG-EPON

Downstream 10G-EPON transmitters generate ~~operates at~~ higher power levels than 1G-EPON, causing interaction between analog RFoG and digital EPON carriers, as discussed in ~~more detail in~~ [stsp]. In effect, analog modulated RFoG carriers are depleted into high power digital carriers of 10G-EPON, causing signal to noise ratio (SNR) degradation and in extreme cases – service outage.

As NG-EPON is expected to support the same power budgets as 10G-EPON and ~~moves to employ higher output power and~~ take advantage of multiple-wavelength access systems, Raman effect mitigation techniques become increasingly important. The toolset (channel link model, see [clm]) developed under IEEE P802.3av *10G-EPON PHY* Task Force accounts for the Raman effect and remains applicable to future NG-EPON development effort, though further analysis is needed in the case that multiple co-propagating wavelengths in the downstream and upstream are required.

Formatted: Heading 3

Commented [MH1]: Added text to make sure it is downstream only – there is no such interaction in the upstream.

Commented [MH2]: This section is strictly focused on Raman mitigation and I suggest we separate it from the remainder of the discussion on transmitters.

Formatted: Heading 3

6.5.2 Optical Transmitters

Editorial Note (to be removed prior to publication): Text on optical transmitters in general is needed, focusing probably on higher power transmitters, their technical feasibility, etc.

6.5.3 Tunable Transmitters

Tunable lasers provide a number of advantages when used in the access network, including:

- A single time provisioning process performed on demand, when the new station comes online and it is provisioned by the OLT;
- A single ONU type (model) used for deployment, irrespective of the actual wavelength used by the ONU in the access network (port). This eliminates inventory and warehouse problems related with maintaining different types and models of ONUs, as well as deploying specific ONU models on specific ODN ports.

As of the time of writing, tunable lasers are relatively mature as far as typical transport applications are concerned, employing monolithically integrated Semiconductor Optical Amplifier (SOA) and Mach-Zender (MZ) modulators, as well as automated testing (individual components, as well as resulting transceiver assembly). The manufacturing yield / efficiency has significantly improved in recent years, resulting in substantial decrease in prices of commercially available tunable lasers, as shown in Figure 1~~Figure 39~~. It can be concluded that the total volume of tunable transceivers shipped in 2013 exceeded the volume of shipped fixed wavelength transceivers, while the cost of tunable transceivers continues to decrease more rapidly than fixed wavelength devices. As of the end of 2013, the cost of tunable XFP-format transceiver reached less than 2 times the cost of a fixed wavelength XFP-format transceiver, providing support for the same distance, as well as power budget.

Editorial Note (to be removed prior to publication): Need a reference for the data.

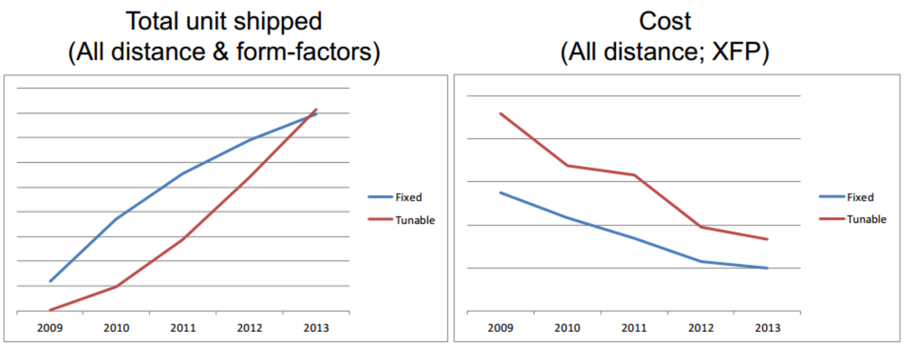


Figure 1~~39~~: Total volume of fixed and tunable transceivers shipped (left image) and observed cost of fixed and tunable transceivers (right image)

Editorial Note (to be removed prior to publication): We can't put actual or average costs in (that's a stupid requirement for this report), but we should at least have a relative scale on the Y-axis to compare fixed v tunable in these charts.

To be successful in access applications, the tunable transceivers require further cost decrease, especially if they are planned for use in ONUs. It is expected that increased volumes generated by NG-EPON deployments in the future, as well as relaxed specifications (center wavelength tolerance, band size, etc.) results in a decreasing cost of such devices, especially when combined with steady progress in automated assembly and testing.

6.6 Optical Receivers

Editorial Note (to be removed prior to publication): The only thing discussed in section 6.6 is tunable filters. We need additional content to talk about the PD or we need to rename this section to Tunable Filters.

Tunable optics enable wavelength tuning features in optical communications systems such as WDM/TWDM based access networks. Tunable receivers work with tunable transmitters to provide access network flexibility and extendibility on legacy ODNs. Furthermore, *colorless* ONUs are highly desirable in optical access networks in order to lower OPEX and enable high volume deployments.

6.6.1 ~~Parameters of t~~Tunable ~~filters~~receivers

~~The t~~Tunable filters are a critical element ~~is an important sub-assembly~~ of a ~~Tunable~~ tunable ~~Receiver~~receiver, required in some candidate architectures for NG-EPON. ~~When a tunable filter is designed, several parameters are used to evaluate the performance of the tunable filter.~~ An ideal tunable filter is a device that can isolate an arbitrary spectral band at an arbitrary wavelength over a broad, continuous spectral range, preferably with a response function that is identical in form at all wavelengths. The set of typical parameters used to characterize an optical filter is presented in Figure 2 and described below:

Commented [MH3]: Fluff – does not add anything to the report.

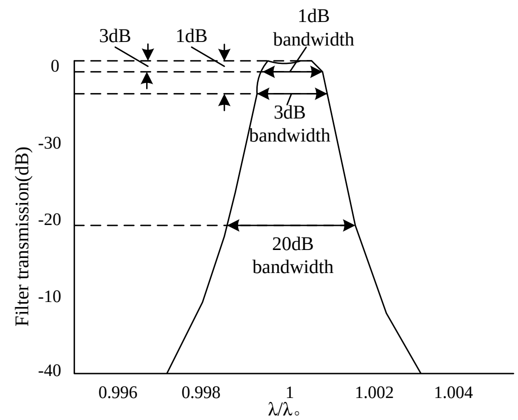


Figure 2~~40~~: Tunable filter and its characteristics

~~The following describes the specific parameters used to evaluate tunable filters.~~

- Insert Loss (IL): the ratio of output optical power and input optical power ~~in~~ (in dB~~)unit, the lower the better~~.
- Polarization Dependent Loss (PDL): the ratio of the maximum and minimum transmission of an optical device with respect to all polarization states. ~~The polarization dependence of the transmission properties of optical components has many sources, in unit of dB, the lower the better.~~
- Return Loss: ~~logarithm of~~ the ratio of input optical power and returned optical power at the same test point~~, in unit of dB, the lower the better~~.
- Tuning Speed: the speed with which the filter can tune to target wavelength. ~~generally classified as s, ms, ns, etc.~~
- Tuning Range: the difference between the shortest and longest wavelength the filter can tune to~~in unit of nm, the larger the better~~.
- ~~High volume production capacity: depending on manufacturing technology.~~
- Passband: the width of the band around the center wavelength where the filter causes minimum loss on the transmitted signal. ~~passband should be as flat as possible to reduce the influence of transmitting wavelength shift. Generally measured at the 1 dB point (see~~ Figure 2~~Figure 40). The larger the better, the edge of the passband should be steep enough to reduce the adjacent channels' crosstalk. Crosstalk's ideal value is -30~-20dB.~~
- ~~Control Mechanism: wavelength tuning and stable mechanism, affecting the tuning speed, precision and wavelength stability.~~

Formatted: Font: Not Bold

Formatted: Font: Not Bold

Formatted: Font: Not Bold

Formatted: Font: Not Bold

Formatted: Font: Not Bold

Commented [MH4]: This is not a filter characteristic

Formatted: Font: Not Bold

Formatted: Font: Not Bold

Field Code Changed

Formatted: Font: Not Bold

Commented [MH5]: This is not a filter characteristics

- Power Consumption: ~~the lower the better~~the power consumption of the wavelength running mechanism in the filter.
- ~~Cost: the lower the better.~~
- ~~Size/Integration capability: the smaller size or the easier integration capability the better.~~

~~6.6.2 Major Types of tunable filter~~

There are three major types of tunable filters, i.e., ~~:~~Fabry-Perot filters, ~~Waveguide~~ waveguide filters and micro-motor filters. A ~~comprehensive~~summary of features of different ~~comparison of~~ tunable filter ~~options~~ types is shown in Table 8.

Table 8: ~~Comprehensive Comparison of Tunable Filter Options~~Different tunable filter options

Filter Types		Tuning Range (nm)	IL (dB)	FWHM (nm)	Channel Spacing/ Isolation	Tuning Speed	~~Pwr~~Power[1]	Cost[3]	Size
Fabry-Perot	Thermal Optical FP Filter	40	2	≤0.5	100 GHz/25 dB	s	Mid	Low	Small
	Liquid Crystal FP Filter	30	3	≤0.5	100 GHz/20 dB	ms	Low	Mid	Mid
	MEMS FP Filter~~[2]~~	221	1.5	≤0.5	100 GHz/20 dB	ms	Low	High	Small
Waveguide	Filter[3][4]	15	4	≤0.5	100 GHz/10 dB	µs	Mid	Mid	Small
	Micro Ring Filter~~[6]~~	20	5.2	≤0.5	100 GHz/60 dB	ms	Low	Mid	Small
Micro-motor	Angle Adjustment Filter	80	0.5	≤0.5	100 GHz/25 dB	ms	Low	High	Large
	Linear Variable Filter	380	2	CWL[5]*1%	100 GHz/25 dB	ms	Low	High	Large
	Cavity Length Adjustment Filter	60	2	≤0.5	100 GHz/20 dB	ms	Low	High	Large

6.6.2 Fabry-Perot filters~~Each is described in the following sections.~~

~~6.6.3 Fabry-Perot filter~~

The Fabry-Perot filter is an optical resonator that confines and stores light energy at selected frequencies. This optical transmission system incorporates feedback, whereby the light is repeatedly reflected within the system and thus circulates without escaping the system. A simple Fabry-Perot filter is comprised of two parallel planar

[1] Power and cost estimates include a TEC, if required for operation under extended temperature conditions
~~[2] Poor anti-shock performance~~
[3] Large crosstalk
[4] Large Insertion Loss
[5] CWL = Center Wavelength

Formatted: Font: Not Bold

Formatted: Font: Not Bold

Commented [MH6]: These are not filter parameters

Formatted: Font: Not Bold

Formatted: Indent: Left: 0.08", Right: 0.08"

Formatted Table

Formatted: Heading 3

mirrors (R_1 and R_2) spaced a fixed distance apart (see Figure 41), and equipped with anti-reflective exterior coatings (AR_1 and AR_2).

The rays travelling between the mirrors are kept perpendicular to the plane of the mirrors via a two-lens system. The lenses are placed outside the mirrors to serve two purposes: first, to establish parallel rays inside the resonance cavity between the mirrors; and second to focus the output light onto the detector following the Fabry-Perot filter.

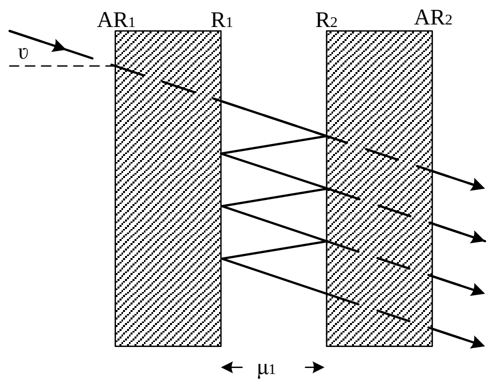
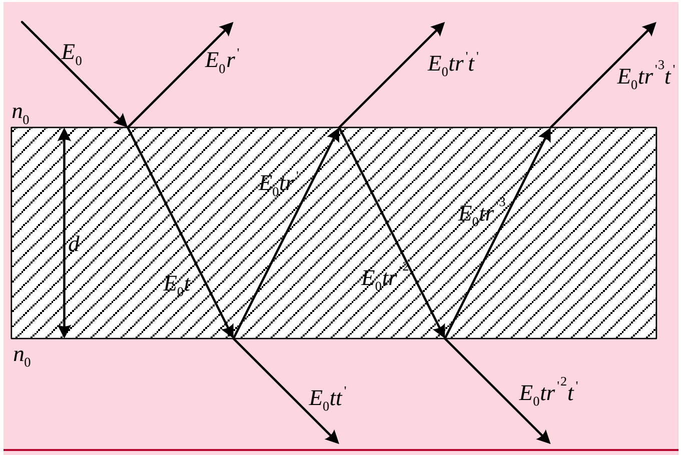


Figure 41: A Fabry-Perot filter

~~Light entering the cavity undergoes multiple reflections. At the resonant wavelengths, the resultant reflected beam destructively interferes with the light reflected from the first plate cavity boundary and all the incident energy, in the absence of absorption, is transmitted.~~



~~**Figure 42: Reflections of light in the Fabry-Perot cavity**~~

Commented [MH7]: Too many details for the report

~~Fabry-Perot filter can be classified into three subtypes, according the tuning method as listed in Table 5.~~

Commented [MH8]: Too many details for the report

~~Table 5: Fabry-Perot filter subtypes~~

~~Tuning Parameter~~	~~Type~~
~~n~~	~~thermal optical,~~ ~~liquid crystal~~ ~~electrical optical~~
~~d~~	~~MEMS~~ ~~Micro-motor~~
~~θ~~	~~Angle adjustment~~

Currently, Fabry-Perot filters implemented in ~~such as~~ thermal optical, liquid crystal, and MEMS ~~tunable filters~~ have already seen commercial applications and are widely used in optical communications. ~~Their features are summarized in Table 6.~~ Thermal optical tunable filters use heating or cooling to control the device's temperature and thus change the refractive index of the Fabry-Perot filter cavity.

Liquid crystal tunable filters are optical filters that use electronically controlled liquid crystal elements to transmit a selectable wavelength of light and exclude others. Often, the basic working principle is based on the Lyot filter but many other designs can be used. ~~Their f~~Features of the primary tunable optical filter types are ~~are~~ summarized in Table 6. ~~This filter type has been applied in optical communications and used in optical channel monitors (OCM), optical add-drop multiplexors (OADM), and wavelength division duplexing (WDD) devices.~~

Table 6: ~~Advantages and disadvantages of~~ Main features ~~different types~~ of Fabry-Perot filters

~~Fabry-Perot f~~**Filter type**	**Advantages**	**Disadvantages**
thermal optical	Small size, easy for integration Low cost materials~~, adaptive high volume application~~ Tuning range can reach 40+ nm~~, or larger, depending on different structures~~ Mature technology with broad application and mature industry chain~~Successful industry production experience, mature industrial chain.~~	Heat induced wavelength tuning and stabilization, driving high power consumption~~Tuning and stabilizing the wavelength by heat, need to reduce power consumption~~ Slow tuning speed, depending on ~~the~~ heater power ~~of the heater~~ and heating method~~.~~
liquid crystal	Mature technology with broad application and ~~, wide application, low cost,~~ mature industry chain Tuning range can reach 30 nm Low power consumption Fast tuning speed	Polarization dependent Temperature sensitivity (~~,~~ needs ~~temperature stability device, such as~~ thermoelectric cooler or heater~~.~~) Large size
MEMS	Fast tuning speed ~~at~~ (μs level) Low power consumption Large tuning range Small size	Complex process, high cost, need to manufacture in high volume capacity Poor anti-shock performance

Field Code Changed

Commented [MH9]: Unnecessary detail for the report – these are transport systems

Commented [MH10]: Table was summarized and unnecessary wordiness was removed

Formatted: Font: Bold

Formatted Table

~~6.6.4~~6.6.3 Waveguide filter

Waveguide tunable filters are based on waveguide structures, including Mach-Zehnder Interferometer (MZI) and micro-ring tunable filter.

MZI (see Figure 43) uses the difference in the length of optical paths to decompose the incoming optical signal and perform selective filtering. The transmission spectrum of single MZI is very wide, so ~~technically~~ multiple MZI are cascaded to achieve a much ~~more narrow~~narrower spectrum filtering capabilities. The resulting large crosstalk as well as technical challenges in the manufacturing process make this technology unsuitable for large-scale application in access networks.

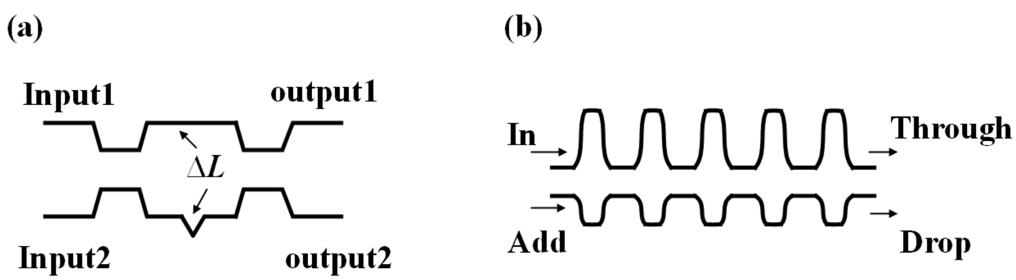


Figure 43: MZI filter schematic diagram

Micro-ring tunable filters (see Figure 44) are based on a waveguide resonator principle. ~~It~~ This filter type has the same characteristic wide spectrum as MZI, thus it is necessary to cascade multiple micro-ring resonators to achieve narrow spectrum filtering capabilities, using one of the available topologies (cascade, serial coupling, or parallel coupling). Advantages are disadvantages of individual topologies of the micro-ring filters are summarized in Table 7.

Commented [MH11]: Added to make sure that it is clear what we are talking about here.

Commented [MH12]: Added to tie in the text on topologies of filters.

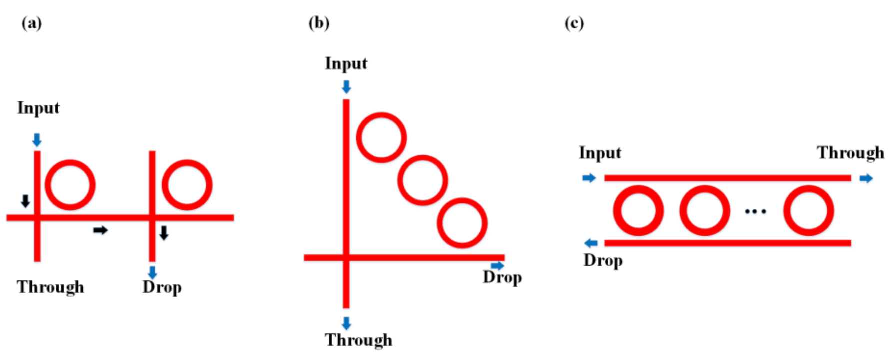


Figure 44: Three topologies of micro ring tunable filters

Table 7: Advantages and drawbacks of the three micro-ring topologies

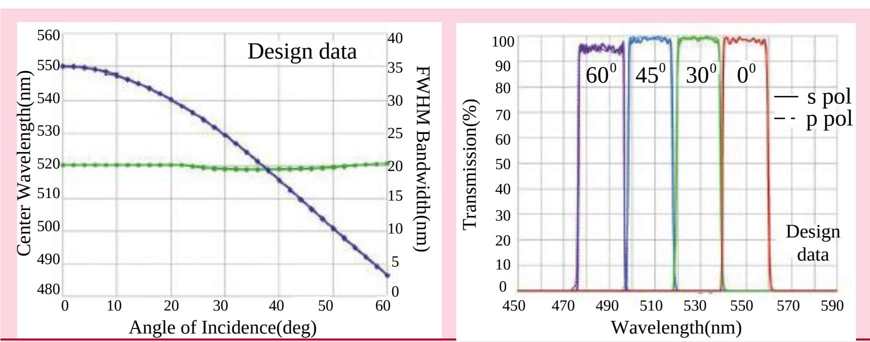
Topology	Advantages	Disadvantages
Cascading	Expansion of FSR Reduced crosstalk	Loss increase due to center wavelength mismatch
Series coupling	Expansion of FSR Flattop pass band	Small fabrication tolerance
Parallel coupling	Flattop pass band	Small fabrication tolerance

~~6.6.5~~6.6.4 Micro-motor filter

A micro-motor filter includes a micro-mechanical element ~~in the form of~~(typically, an electrical motor)~~,~~ changing the properties of the ~~given~~ filtering cavity. There are several types of micro-motor filters, including linear variable, angle adjustment, cavity length adjustment filters.

Linear variable micro-motor filters change the transmission (pass-band) characteristics of the filter ~~unit~~ along with the spatial location of the filtering element. This technology is relatively mature and features a large tuneability range, low insert loss and millisecond-level tuning speed. Drawbacks include large size, high cost, and large full width at half maximum.

Angle adjustment tunable filters feature a special thin-film filter which is ~~then~~ tuned using a micro-motor by adjusting the angle of incident light ~~using a micro-motor~~. The characteristics of this filter type include relatively mature technology, large tuning range, low insert loss, large size, and high cost. ~~A typical spectrum charactsristic of an angle adjustment tunable filter is shown in Figure 45.~~



~~Figure 45: Spectrum character of angle adjustment tunable filter~~

Cavity length adjustment tunable filters use a micro-motor to change the length of the filter cavity to adjust the filtering wavelength (see Figure 46). These filters have low insertion loss, thermal stability, high reliability, and relatively large size.

Formatted Table

Formatted: Justified, Don't keep with next

Commented [MH13]: Since we do not compare it with anything else, it is questionable whether we need it at all

Formatted: Normal

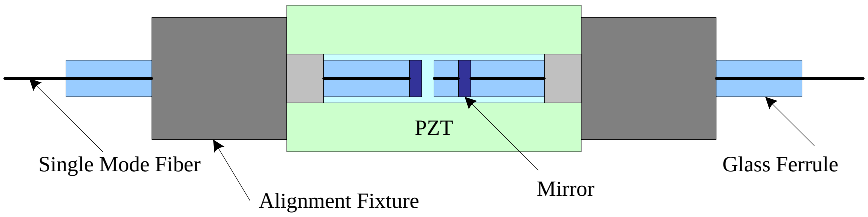


Figure 46: Cavity length adjustment tunable filter

~~6.6.6 Summary of different types of tunable filters~~

~~A comprehensive comparison of tunable filter options is shown in Table 8.~~

~~Table 8: Comprehensive Comparison of Tunable Filter Options~~

~~Filter Types~~		~~Tuning Range (nm)~~	~~IL (dB)~~	~~FWHM (nm)~~	~~Channel Spacing/ Isolation~~	~~Tuning Speed~~	~~Pwr~~[6]	~~Cost~~[3]	~~Size~~
~~Fabry-Perot~~	~~Thermal Optical FP Filter~~	~~40~~	~~2~~	~~<0.5~~	~~100 GHz/25 dB~~	~~s~~	~~Mid~~	~~Low~~	~~Small~~
	~~Liquid Crystal FP Filter~~	~~30~~	~~3~~	~~<0.5~~	~~100 GHz/20 dB~~	~~ms~~	~~Low~~	~~Mid~~	~~Mid~~
	~~MEMS FP Filter~~[7]	~~221~~	~~1.5~~	~~<0.5~~	~~100 GHz/20 dB~~	~~ms~~	~~Low~~	~~High~~	~~Small~~
~~Waveguide~~	~~Filter~~[8][9]	~~15~~	~~4~~	~~<0.5~~	~~100 GHz/10 dB~~	~~μs~~	~~Mid~~	~~Mid~~	~~Small~~
	~~Micro Ring Filter~~[6]	~~20~~	~~5.2~~	~~<0.5~~	~~100 GHz/60 dB~~	~~ms~~	~~Low~~	~~Mid~~	~~Small~~
~~Micro-motor~~	~~Angle Adjustment Filter~~	~~80~~	~~0.5~~	~~<0.5~~	~~100 GHz/25 dB~~	~~ms~~	~~Low~~	~~High~~	~~Large~~
	~~Linear Variable Filter~~	~~380~~	~~2~~	~~CWL~~[10]~~*1%~~	~~100 GHz/25 dB~~	~~ms~~	~~Low~~	~~High~~	~~Large~~
	~~Cavity Length Adjustment Filter~~	~~60~~	~~2~~	~~<0.5~~	~~100 GHz/20 dB~~	~~ms~~	~~Low~~	~~High~~	~~Large~~

6.7

[6] ~~Power and cost estimates include a TEC, if required for operation under extended temperature conditions~~
[7] ~~Poor anti-shock performance~~
[8] ~~Large crosstalk~~
[9] ~~Large Insertion Loss~~
[10] ~~CWL = Center Wavelength~~

Field Code Changed