

# SDN Control of Amplification Stages in Multi-Band Optical Networks

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**Abstract** A YANG model for multi-band amplifiers is proposed. Thulium Doped Fiber Amplifier (TDFA) characterization is performed, then automated control configuring TDFA based on traffic load and C+S transmission are experimentally demonstrated. ©2023 The Author(s)

## Introduction

C+L systems are already deployed in several countries (e.g., in Europe, Middle East, and America) [1], thus, network upgrades to the S-band or other bands are under investigation [2],[3]. There are several factors to be considered in multi-band networks (e.g., the impact of stimulated Raman scattering [3][4]). One of the key issues is the lack of a single Rare-Earth Doped Fiber providing optical amplification over the multiple transmission bands [5]. As an example, Erbium Doped Fiber Amplifier (EDFA) is suitable in C and L bands. On the other hand, Thulium Doped Fiber Amplifiers (TDFAs) are identified to be appropriate for the S-band [6] and are commercially available [7]. This differentiation of the amplification technology per band has implications on both network architecture and control. First, an *amplification stage* needs to be re-built (as in Fig. 1): transmission bands should be de-multiplexed and each one directed to the proper amplifier (e.g., TDFA for S, Nd<sup>3+</sup> for E [3]), thus re-multiplexed to be launched in the fiber. Then, the control system should be able to control different amplification technologies, probably each one with different properties and configuration possibilities.

In this paper, we present a Software Defined Networking (SDN) control for amplification stages in multi-band optical networks. An experimental testbed is set up including EDFA and TDFA, both controlled through the NETCONF protocol and YANG data model. We present a YANG data model for amplification stages in multi-band networks, that enhances

the standard OpenConfig data model [8]. Then, an automated control system configuring amplifiers (TDFA in particular) depending on the number of channels is presented. Such automated control is based on an experimental characterization of the TDFA. Finally, an experiment is presented including four amplified channels in C-band and three amplified channels in S-band with error-free transmission performance over 40 km span.

## Amplification stage control

This section provides the implementation details of the SDN control of optical amplifiers in the multi-band scenario, with a particular focus on TDFA [7]. The adopted TDFA is equipped with three pump laser diodes (pump-LDs): a main-LD and two sub-LDs. The device offers Automatic Light Control (ALC) of the main-LD, enabling control of the amplifier by configuring a target output power, which however fluctuates depending on the input power. Therefore, by setting the pumping current values of the remaining two sub-LDs, it is possible to bring the power to the target level. Automatic Gain Control (AGC) is not supported by the device, therefore its mode cannot be configured to constant gain. Given that the behaviour of TDFA (i.e., output power) depends on the input power level (thus, also on the number of input channels), on sub-LDs pumping current values, and on the wavelengths, an experimental characterization of the TDFA is performed in order to design and implement the TDFA control. Such characterization will permit to properly set the pumping according to the target output power and the input signals at the TDFA.

The TDFA is characterized by the input signal power granularity of 5 dBm, covering a range from -35 dBm to 0 dBm. The input power variation has been achieved through the use of a Variable Optical Attenuator (VOA). Fig. 2 provides a detailed depiction of the sub-LDs (pump-LD-2 and pump-LD-3) current values (in mA) when the overall input power is -15 dBm. For example, to achieve the target overall output power of 10 dBm, the pump-LD-2 should be

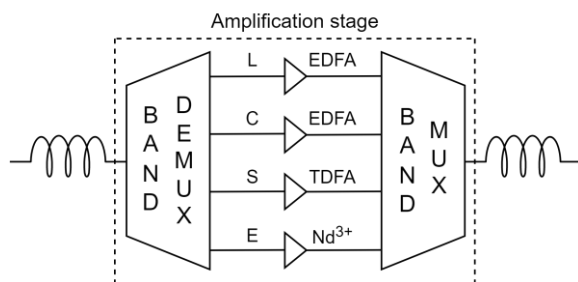


Fig. 1: Amplification stage in multi-band networks.

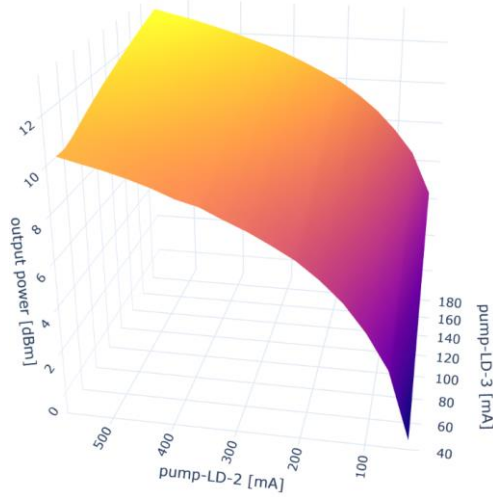


Fig. 2: TDFA Characterization, input power = -15 dBm.

configured to 210 mA, while the pump-LD-3 should be set to 140 mA. It is worth noting that the variation in the current of pump-LD-3 has a greater impact on the output power compared to pump-LD-2. A lookup table implemented in Python has been utilized for mapping the input power and the target output power values to the corresponding sub-LDs pumping currents. This way the control plane can apply the correct configuration of the pump-LDs, ensuring a constant target output power. Note that the proposed approach may also support specific power optimization strategies [9][10] (e.g., if configuring per channel attenuation is supported also by wavelength selective switches in the S-band).

REST API interface is used by the NETCONF agent (i.e., a local controller of the device) to configure and collect the monitored parameters from TDFA device. Finally, the proposed YANG model, shown in Fig. 3, provides a comprehensive and structured approach to enable the SDN control of an amplification stage (including TDFA) in multi-band networks.

The model enhances the standard OpenConfig data model, adding a list of dedicated amplifiers (e.g., one per band), enabling configuration and monitoring of their parameters, such as type (e.g., TDFA), mode (e.g., CONSTANT\_POWER), target gain and target output power. It also adds a list of pump-LDs, with their corresponding bias currents and driving modes, and other operational parameters such as the temperature and Thermoelectric Cooling (TEC) current. Furthermore, the proposed model provides state data including operating band, total input and output power, and noise figure. This YANG model enables the SDN control of amplifiers

```
module: openconfig-multiband-optical-amplifiers
+---rw multiband-optical-amplifiers
+---rw optical-amplifier
+---rw amplifier* [id]
+---rw id -> ../config/id
+---rw config
+---rw id? uint32
+---rw name? string
+---rw amp-mode? identityref
+---rw target-output-power? decimal64
+---rw max-output-power? decimal64
+---rw target-gain? decimal64
+---rw active? boolean
+---rw laser-diode-pumps
+---rw pump-LD* [pump-id]
+---rw pump-id uint32
+---rw pump-bias-current? decimal64
+---rw pump-mode? identityref
+---ro state
+---ro id? uint32
+---ro name? string
+---ro operating-band
+---ro amplifier-band? identityref
+---ro lower-frequency? oc-opt-types:frequency-type
+---ro upper-frequency? oc-opt-types:frequency-type
+---ro type? identityref
+---ro amp-mode? identityref
+---ro target-output-power? decimal64
+---ro max-output-power? decimal64
+---ro target-gain? decimal64
+---ro active? boolean
+---ro laser-diode-pumps
+---ro pump-LD* [pump-id]
+---ro pump-id uint32
+---ro pump-bias-current? decimal64
+---ro pump-mode? identityref
+---ro pump-temperature? decimal64
+---ro pump-TEC-current? decimal64
+---ro input-power-total? decimal64
+---ro output-power-total? decimal64
+---ro noise-figure? decimal64
+---ro optical-return-loss? decimal64
+---ro fiber-type-profile? identityref
+---ro component? leafref
+---ro ingress-port? leafref
+---ro egress-port? leafref
```

Fig. 3: YANG model for multi-band amplification stages.

supporting configuration and monitoring via <edit-config> and <get> NETCONF messages, respectively.

## Experimental validation and results

This section describes the experimental validation of the automated control system that configures the TDFA according to the input signals. In order to validate the correct control plane operation, up to three channels in the S-band (at 1508 nm, 1510 nm and 1512 nm) are aggregated and amplified. The exploited TDFA operates in power mode: i.e., constant output power. Thus, whenever new channels are added or existing ones are dropped, the TDFA requires (re-)configuration to ensure proper amplification per channel (e.g., 0 dBm/channel at the output of TDFA). Note that, even with EDFAs, which typically work in gain mode (i.e., constant gain), a proper control of the power mode is useful given that, when a new link is added to the network, the output power at EDFAs is typically incrementally increased to avoid any possible issue (e.g., power peaks,

Tab. 1: TDFA configuration based on the traffic load.

# ch	power [dBm]		pump-bias-current [mA]	
	input	output	id = 2	id = 3
1	-19.74	0	50	50
2	-16.79	3	150	60
3	-15.13	5	250	70

```

<multiband-optical-amplifiers xmlns="http://openconfig.net/yang/optical-amplifier">
  <optical-amplifier>
    <amplifier>
      <id>1</id>
      <config>
        <id>1</id>
        <name>TDFA</name>
        <amp-mode>CONSTANT_POWER</amp-mode>
        <target-output-power>3.0</target-output-power>
        <active>true</active>
        <laser-diode-pumps>
          <pump-LD>
            <pump-id>2</pump-id>
            <pump-bias-current>150.0</pump-bias-current>
          </pump-LD>
          <pump-LD>
            <pump-id>3</pump-id>
            <pump-bias-current>60.0</pump-bias-current>
          </pump-LD>
        </laser-diode-pumps>
      </config>
    </amplifier>
  </optical-amplifier>
</multiband-optical-amplifiers>

```

**Fig. 4:** NETCONF <edit-config> message.

perturbations of existing channels). Tab. 1 shows the required configuration of the target output power and the appropriate pumping current values of sub-LDs based on the traffic load (i.e., number of channels, # ch) and monitored input power. For example, the input power of a single S-band channel at 1508 nm is -19.74 dBm. In order to ensure that the target output power is 0 dBm, pump-LD-2 and pump-LD-3 need to be configured to 50 mA each. As the traffic load increases, another channel at 1510 nm is added, resulting in the input power of -16.79 dBm. After a change in the input power and the number of channels to be amplified, the automated control system adapts to the new network scenario and adjusts the TDFA accordingly. This is achieved by sending a NETCONF <edit-config> message (shown in Fig. 4) – which is based on the YANG model in Fig. 3 – to reconfigure the TDFA and maintain a constant output power of 0 dBm per channel.

Finally, an experimental validation of C+S transmission is presented in the context of the testbed reported in Fig. 5. Three laser sources, S1, S2 and S3, operating in the S-band at 1520.315 nm, 1520.480 nm, and 1528 nm respectively, are coupled and amplified by a Semiconductor Optical Amplifier (SOA) due to the low output power of the sources. Next, an I/Q modulator, that operates over linear polarized signals, is used for the generation of QPSK format. Dual Polarization (DP) is obtained by splitting signals into two orthogonal polarizations that are then de-correlated with regard to each other by utilizing a delay line (POL MUX). The signals are then finally

**Tab. 2:** C+S transmission based on the traffic load.

Multi-band network scenario	OSNR of the observed S-band channel [dB]
1 S + 4 C	15
2 S + 4 C	18
3 S + 4 C	17

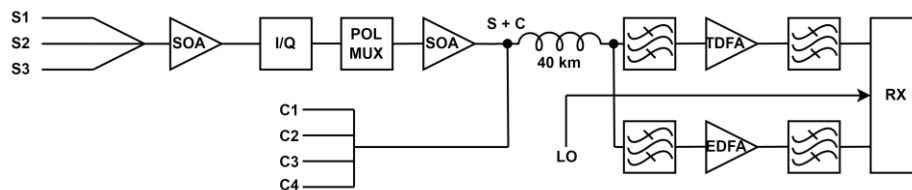
combined and DP-QPSK channels are achieved. Another SOA is exploited for the S-band channels to compensate for the losses at the transmitter side (i.e., I/Q modulator); then, coupling with four channels operating in the C-band is done. After launching C+S channels in 40 km of standard single mode fiber, they are split into two ends for further extraction of the bands, using a splitter with a 50:50 splitting ratio. Both splitter ends contain C+S channels, and are then directed to the proper filters for separating the C and S bands (BAND DEMUX in Fig. 1), before entering the EDFA and TDFA, respectively. Therefore, once the S-band is extracted by filtering out the C-band channels, the three S-band channels are amplified by leveraging the TDFA. Finally, after traversing the second filter, a single S-band channel reaches the coherent Rx. Error-free transmission was achieved and the OSNR values depending on the traffic load (i.e., number of channels in the S-band) are presented in Tab. 2 for a S-band signal under test. The OSNR of the observed S-band channel increases when a second S-band channel is added because the noise of the utilized SOAs is reduced.

## Conclusions

This work proposes the YANG data model for amplification stages in multi-band networks. The automated control of the characterized TDFA is experimentally demonstrated. Finally, the experimental validation of an SDN multi-band C+S transmission is shown.

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**Fig. 5:** Experimental testbed

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