In Situ Design Method for Multichannel Gain of a Distributed Raman Amplifier With Multiwave OTDR

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***Abstract*—We demonstrate a novel approach for the measurement of pump/signal waves interaction in the Raman amplifier (RA), with the use of multiwave optical time-domain reflectometry. With the application of obtained pump-evolution profiles to algorithms based on effective length recalibration, the multichannel Raman gain can easily be predicted with excellent accuracy for the undepleted, distributed RA. As a further extension of this algorithm, an *in situ* semi-analytic Raman-gain design method is also demonstrated.**

***Index Terms*—Gain spectrum, optical time-domain reflectometry (OTDR), Raman amplifier (RA), wavelength-division multiplexing (WDM).**

I. Introduction

WITH the advance of high-power laser diode technology, the Raman amplifier (RA) has become a practical means to meet the increasing demands of transmission capacity and distance. In addition to its distinctive flexibility in gain-band allocation, the gain bandwidth of RA also can be easily extended with the inclusion of multiple pumps [1]. Seemingly simple in principle, the optimization process for the gain-bandwidth design for RA in a real wavelength-division-multiplexing (WDM) system requires extensive efforts with much considerations on many factors—pump interaction, polarization dependency, double Rayleigh scattering, and detailed information on fiber parameters. While there have been many efforts to establish a good optimization algorithm using numerical analysis [2]–[4], the exhaustive complexity of theoretical modeling, with too large a number of necessary parameters, which are hard to access, make its practical application to the installed lines difficult. For this reason, optimization methods based on experimental measurement of indirect data sets such as link-loss profile [5] and noise power [6] with corresponding analysis, have been proposed.

In this letter, we demonstrate a novel design technique for the first time (within the authors' knowledge), with a direct*in situ* measurement of pumps/signal evolution inside the Raman fiber, based on a modified, multiwave optical time-domain reflectometry (OTDR) technique. With the measured pump evolution, the multipump-gain spectrum can be calculated using a simple analytic integration and summation of single-pump gain profiles. The discrepancy between the measured, and calculated gain spectrum was less than 0.5 dB over the gain bandwidth. Extension of the concept to the semi-analytical design of the multichannel gain shows excellent agreement between the target and measured Raman gain spectrum.

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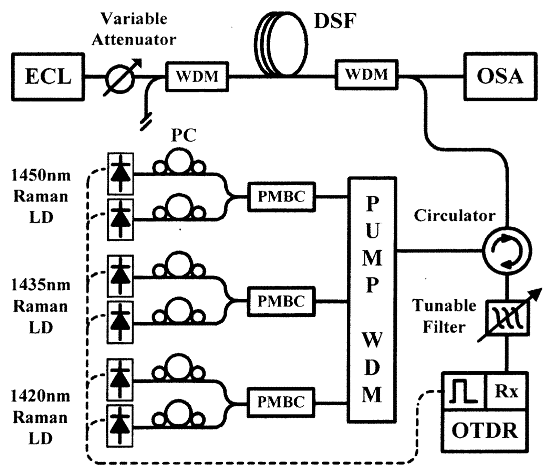

Fig. 1. Setup (ECL: tunable external cavity laser, PC: polarization controller, PMBC: polarization maintaining beam combiner).

II. Experimental Setup

Fig. 1 shows the set up for the measurement of Raman-pump evolutions in the transmission fiber. Pump laser diodes (LDs) at 1420, 1435, and 1450 nm were used in the experiment. Two pump diodes were combined for each wavelength, with a polarization maintaining beam combiner. In the analysis mode, the Raman pump LDs were modulated to give a pulse, to work as an OTDR source with the synchronous triggering signal from the modified OTDR [7], [8] transmitter end. A tunable Fabry–Pérot (FP) filter was also employed to block those interband Rayleigh back-scattered light from other pump sources, which otherwise adds background noise to the OTDR receiver. Forty kilometers of dispersion-shifted fiber (DSF) made of two 20-km spools (connected by fusion splice) was used as both transmission fiber and distributed Raman gain medium. A tunable external cavity laser was used as a Raman gain probing signal with a variable attenuator. By successively using each pump diode as the OTDR light source first, the loss profiles at each pump wavelength were characterized. During the measurement, the pump diode in the OTDR mode was modulated to launch the optical pulse with a 1-μs width at every 0.5 ms. Solid lines in Fig. 2 correspond to the measured intrinsic fiber loss profile at each pump wavelength (with all other pumps and probing signal off).

In the *other mode* of characterization, we on–off modulated the probing pump OTDR with all the other Raman pumps in continuous-wave (CW) mode. Dotted lines show the measured evolution of multiple pumps inside the transmission fiber in-

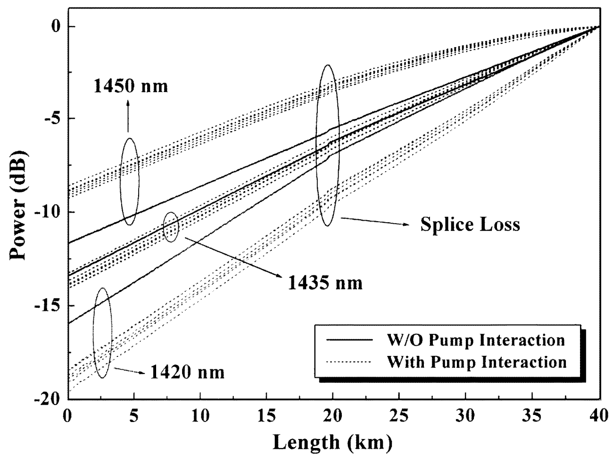

Fig. 2. Measured Raman pump evolution trace in the transmission fiber by p-OTDR (at different CW pump settings).

teracting with each other at various pump-magnitude combination sets. This mode of operation can also be extended to the data-signal wavelength for the signal evolution characterization. As can be seen in Fig. 2, the pump-evolution profile for 1450 nm has been shifted upward, from power transfer from the 1420-nm, and 1435-nm pump. In contrast, the evolution profile of 1420 nm has been shifted downward, as a result of power depletion to longer wavelength pumps. For the case of 1435 nm, due to the depletion plus amplification from the longer/shorter wavelength pump, the evolution lines did not show much deviation from the intrinsic loss profile. It is worth noting that the splicing loss at 20 km and the differences in the loss coefficient between two sets of identical DSF spools are evidently shown in all evolution profiles, providing real fiber characteristics otherwise hard to get in real field.

III. Analysis

Noting that most RA applications are for the extension of transmission distance to achieve higher optical signal noise ratio (OSNR), and further recognizing that the pump depletion by the signal is rather negligible in this domain, it is possible to rescale the effective lengths of pumps L_{eff} by applying the measured OTDR pump evolution to the following equation (1), with a simple numerical integration [5], [7]

$$L_{\text{eff}} = \int_0^L P_P(z)/P_P(L)\, dz. \tag{1}$$

Table I shows the calculated L_{eff} with different pump power sets. For 1450 nm, L_{eff} was greatly increased from 14.6 km to over 21.5 km. With the power transfer from those shorter wavelength pumps, 1450-nm waves reach much further into the transmission fiber, enhancing the length in which the Raman amplification process occurs effectively. In contrast, L_{eff} at 1420 nm was reduced from 11.9 km down to 8.8 km. Aside from these observations, we also recall the equation for the Raman gain evolution

$$G_{\text{on/off}} = \frac{P_S(L)}{P_S(0)} \exp(-\alpha_S L) = \exp\left(\frac{g_0 P_P(L) L_{\text{eff}}}{2A_{\text{eff}}}\right) \tag{2}$$

TABLE I

Rescaled Pump Effective Length L_{eff} Under Interaction

		Pump Power (mW) & L_{eff}				
1420nm	1435nm	145		120	80	off
	1450nm	115	80	115		
	L_{eff} (km)	8.8	9.3	9.1	9.5	11.9
1435nm	1420nm	145		120	80	off
	1450nm	115	80	115		
	L_{eff} (km)	13.1	14.0	12.9	12.5	13.5
1450nm	1420nm	145		120	80	off
	1435nm	120	80	145		
	L_{eff} (km)	21.5	20.4	21.3	20.0	14.6

where $P_S(z)$ is the signal power at position z, α_S the fiber loss coefficient, g_0 the Raman gain coefficient, and A_{eff} the effective area, respectively. Now using

$$\frac{g_0}{2A_{\text{eff}}} = \frac{\ln G_{\text{on/off-R}}}{L_{\text{eff}\text{-}R} P_{P\text{-}R}(L)} \tag{3}$$

we can rewrite the on–off gain in equation (2) as

$$G_{\text{on/off}} = (G_{\text{on/off-R}}) \frac{P_P(L) L_{\text{eff}}}{P_{P\text{-}R}(L) L_{\text{eff}\text{-}R}}. \tag{4}$$

For this, it is worth noting that the wavelength-dependent Raman coefficients $g_0/2A_{\text{eff}}$ can easily be calculated by using (3) with a certain input reference Raman-pump power $P_{P\text{-}R}(L)$ and calculated effective length $L_{\text{eff-R}}$ based on the OTDR assessment data, together with the measured single-pump gain $G_{\text{on/off-R}}$. By using (4), any unknown gain $G_{\text{on/off}}$ at arbitrary pump power $P_P(L)$ can be easily calculated from L_{eff} (measured by OTDR).

IV. Application

Fig. 3 shows the measured and reconstructed multipump gain as well as single-pump gains spectra measured with different pump sets, which were used as reference data sets in (4). The calculated multipump Raman-gain spectra by this algorithm and the rescaled gain contribution—by L_{eff}—from each pump wavelengths are shown in Fig. 3 as filled circles. As can be clearly seen in the figure, the gains provided by two lower wavelength pumps were reduced, while the gain provided by upper wavelength pumps have been significantly increased through pump interaction recalibration. With all the dynamics related with different fiber parameters already included in the experimental characterization mode, the discrepancy between measured/calculated multipump gain was under 0.5 dB up to -3 dBm of output signal power.

Observing the nature of Raman gain under pump interaction, and verifying the validity of the effective-length recalibration technique for assessment, we now extend our observations to the semi-analytic design of multichannel Raman-gain profiles. With the inhomogeneous property of the Raman process, the Raman gain G_{t_dB} at a certain wavelength λ can be constructed within first order, from a simple summation of gain values which are provided by each nth pump G_{n_dB}, as follows:

$$G_{t\_\text{dB}}(\lambda) = \sum_{n=1}^{M} G_{n\_\text{dB}}(\lambda) \tag{5}$$

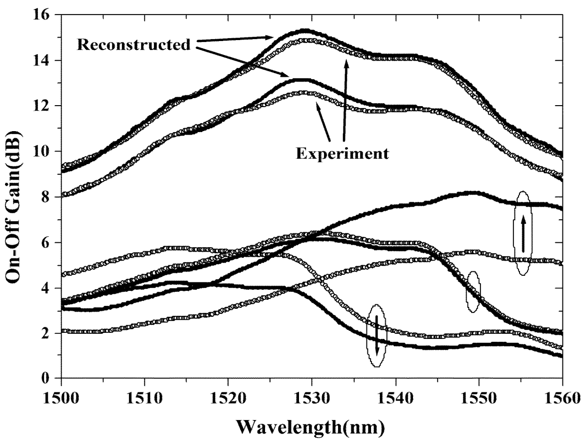

Fig. 3. Measured/reconstructed gain spectrum for single/multipump source (hollow: experiment, filled: reconstruction, pump power of 145/145/115 mW and 145/100/115 mW at 1420, 1435, 1450 nm, respectively).

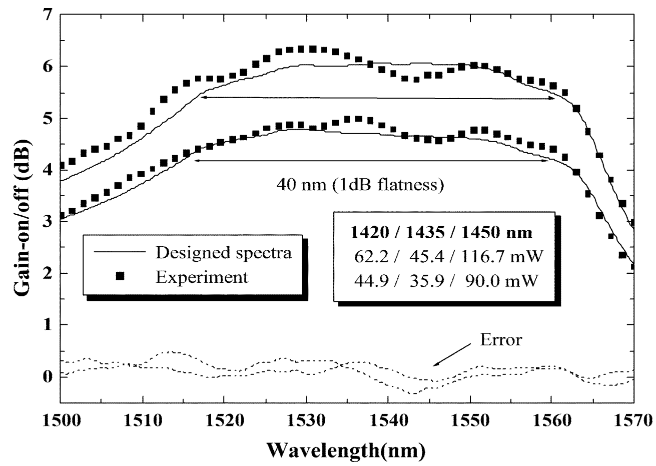

Fig. 4. Design constraints, designed target spectra, and experimentally measured Raman-gain spectrum.

where M is the number of used pumps. From (2) and (5), using the measured-gain coefficient and L_{eff}, the required set of single-pump gain spectra satisfying a set of target multi-pumped-gain-profile constraints (flatness, level, bandwidth, wavelength) can be found first, which can be then used to further derive a necessary "effective" pump power set. In other words, we now move the pump interaction effect from the recalibration of effective *length* to effective *pump power*. To back-trace the "original" pump power injected into the fiber, we derived/used the following simple relationship between the effective/original pump powers:

$$P_{\text{org}},\, n = P_{\text{eff}},\, n/G_t(\lambda_{P_n}) + \sum_{i=n}^{M-1}\left(P_{\text{eff}},\, i+1 - \frac{P_{\text{eff}}\, i+1}{G_t(\lambda_{P_{i+1}})}\right) \cdot \frac{G_{n\_\text{dB}}(\lambda_{P_{i+1}})}{G_{t\_\text{dB}}(\lambda_{P_{i+1}})} \cdot \frac{\lambda_{P_{i+1}}}{\lambda_{P_n}}. \quad (6)$$

Here, the first/second term on the right-hand side means amplification/depletion by the shorter/longer wavelength pumps, where $P_{\text{org}}\, n$ is the original injected pump power set $(n = M,\, M-1,\, \ldots,\, 1)$, and $P_{\text{eff}}\, n$ is the effective pump power providing the target spectrum, after the pump interaction. Using this algorithm and the measured effective length, we tried to find out the corresponding pump combinations for the target–gain spectrum, with (6). To get the necessary pumping conditions for the target-gain profile, we used a relaxation method both on the pump wavelength and pump powers, while minimizing the error function under the additional restrictions (number of pump wavelength, total pump power etc.). For the whole optimization process, the required CPU time with a conventional PC did not take more than a few seconds, for even harder design criteria of up to 1-dB flatness over 100 nm (with 12 wavelength). As is clearly seen in Fig. 4, the experimentally measured flattened–gain profile with different average gain level—limited by the number of available LDs—provided by multiwavelength pump combinations satisfying a given design constraints found by the proposed process showed excellent agreement with the designed target spectrum with less than 0.5 dB of error function.

V. Conclusion

We proposed and demonstrated a novel multiwave OTDR technique and algorithm for the *in situ* measurement of multi-pumps/signal evolution, which can be used for the assessment of pump/signal evolution in lumped/depleted RA, or for the design of multichannel Raman-gain spectrum for preamplifier applications. With the set of measured pump-evolution profiles and only one reference data, the multichannel-gain spectrum could be semi-analytically designed *in situ*, for any installed fiber. Together with the other accessible fiber data sets from this technique, this approach also can be extended further to construct intelligent RA which can self adjust their parameters on the operational condition shift.

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