Design of Raman-parametric fiber amplifier for wavelength division multiplex transmission system

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We optimize the novel configuration of a hybrid fiber amplifier — Raman assisted-fiber-based optical parametric amplifier (R-FOPA), in which the parametric gain and Raman gain profiles are combined to achieve a flat composite gain profile. The pump powers and the fiber length in the hybrid amplifier are effectively optimized by genetic algorithm (GA) scheme. The optimization results indicate that the R-FOPA can achieve a 200-nm flat bandwidth spectrum with the gain of 20 dB and ripple of less than 4 dB.

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As wide-band optical fiber amplifiers are indispensable devices for the further development of large-capacity optical networks, various researches have been conducted to propose ideal amplifier configurations. Fiber Raman amplifier (FRA) and fiber-based optical parametric amplifier (FOPA) have attracted much research interest for their low noise figure and flexible center wavelength[1,2]. However, it is quite complex in allocating wavelength division multiplex (WDM) pump powers at different wavelengths for FRA to obtain a broad bandwidth, and a single-section FOPA has an apparent gain imbalance across a large frequency range. In response to these limitations, a multi-section design has been proposed[3−5], which can efficiently widen and flatten the gain spectrum by using several highly nonlinear fibers and ultra-flat dispersion fibers with different zero dispersion wavelengths (ZDWs) and in different lengths.

In this paper, we optimize the novel design of fiber amplifier — Raman assisted-FOPA (R-FOPA), in which the parametric gain and Raman gain profiles are combined to achieve a wide and flat gain spectrum. Genetic algorithm (GA), which has been proved successfully in optimal design of both FRA and FOPA[4,6], is extended to effectively optimize the pump powers for the hybrid amplifier to achieve a flat composite gain profile.

Based on the four-wave mixing theory, the gain of FOPA is calculated by[7]

$$G_{\mathrm{OPA}} = 1 + \left[\frac{\gamma P_{\mathrm{OPA}}}{g_{\mathrm{OPA}}}\sinh\left(g_{\mathrm{OPA}}L\right)\right]^2, \tag{1}$$

where γ is the nonlinear coupling coefficient, L is the fiber length, P_{OPA} is the parametric pump power, g_{OPA} is the parametric gain coefficient determined by

$$g^2_{\mathrm{OPA}} = -\Delta\beta\cdot\left(\frac{\Delta\beta}{4} + \gamma P_{\mathrm{OPA}}\right), \tag{2}$$

in which the small propagation mismatch $\Delta\beta$ is expressed by

$$\Delta\beta = -\frac{2\pi}{\lambda_0^2}\frac{\mathrm{d}D}{\mathrm{d}\lambda}\left(\lambda_{\mathrm{p}} - \lambda_0\right)\left(\lambda_{\mathrm{p}} - \lambda_{\mathrm{s}}\right)^2, \tag{3}$$

where λ_{p}, λ_{s}, λ_0 are the wavelengthes of pump, signal, and zero-dispersion respectively, and $\mathrm{d}D/\mathrm{d}\lambda$ is the slope of the dispersion at λ_0. When we define $k = 2\pi/\lambda_0^2\cdot \mathrm{d}D/\mathrm{d}\lambda\cdot(\lambda_{\mathrm{p}} - \lambda_0)$, $\Delta\beta$ can be rewritten as $k\cdot(\lambda_{\mathrm{p}} - \lambda_{\mathrm{s}})^2$.

The gain of FRA is based on the stimulated Raman scattering (SRS) in the fiber, and the most important of which, for the purpose of present consideration, are the pump-to-pump and pump-to-signal SRS. In steady state, this gain profile is described by[8]

$$G_{\mathrm{Raman}} = \exp\left(\frac{g_{\mathrm{Raman}}P_{\mathrm{Raman}}L}{A_{\mathrm{eff}}}\right), \tag{4}$$

where P_{Raman} is the pump power, A_{eff} is the fiber effective area, and g_{Raman} is the Raman gain coefficient. g_{Raman} used in the following calculation referres to Fig. 1 in Ref. [8]. The bandwidth for a single FRA is limited by the Raman shift, which is up to 170 nm for the telluride-based fiber (maximum $g_{\mathrm{Raman}} = 55\ \mathrm{W^{-1}\cdot km^{-1}}$) and 100 nm for the silica-based fiber (maximum $g_{\mathrm{Raman}} = 3.5\ \mathrm{W^{-1}\cdot km^{-1}}$).

Both FOPA and FRA have the advantage that the center wavelength of the amplification bandwidth is dependent on λ_{p} and their gain shapes can be controlled by the use of multiple pumps. Moreover, the gain profiles of one-pump FOPA and FRA have different peak features, which can be utilized to complement each other in a hybrid structure.

Here we present an optimized design of R-FOPA whose schematic configuration is shown in Fig. 1. The hybrid amplifier is forward-pumped by a parametric pump laser diode (LD) and back-pumped by one-above Raman pump LDs. The fiber, as the amplification medium, can be

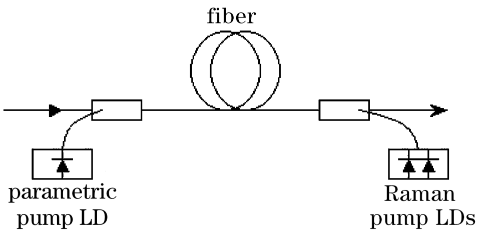

Fig. 1. Schematic configuration of R-FOPA.

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either silica or telluride-based.

GA is applied to optimize the composite gain spectrum. Fixing the wavelengths of parametric pump ($\lambda_{\mathrm{P-FOPA}}$) and Raman pumps ($\lambda_{\mathrm{P-Raman}}$), we adjust the fiber length and the pump powers for the best results.

GA scheme starts with the chromosome representation in the "individual", a group of which constitutes a "population". In our work, each individual (population$_j$) consisted of $N+1$ "chromosomes", corresponding to different powers required in the forward parametric pump, $N-1$ backward Raman pumps, and the fiber length, i.e., $P_1, P_2, \cdots, P_N$ ($N = 2, 3, 4$), L. The individuals are described by binary code strings. As the first generation, the initial population is randomly created. The population size (the number of individuals in one population) is set to 100. Both gain and bandwidth are set to be the optimal objects. The gain ripple referres to the fitness function

$$E = \frac{1}{\frac{1}{G_0}\sqrt{\frac{1}{N}\sum\limits_{n=1}^{N}\left[G_0 - G\left(\lambda_n\right)\right]^2}}, \tag{5}$$

where G_0 is the expected on/off gain value.

Each successive generation is produced after experiencing the process of selection, crossover, and mutation. The selection mechanism implemented in our work is the roulette wheel method. The crossover rate is 85%, specifying the odds that the genes in two chromosomes will crossover to produce two new individuals. The mutation rate is initially set at 8% and would change during the evolution process. In the case of bit representation, the mutated gene in one individual simply flippes to produce a new individual. GA works through generations after generations, selecting and reproducing parents until the specified maximum number of generations is reached.

The optimization is based on the basic configuration in Fig. 1. We start with one forward parametric pump and one backward Raman pump, and the fiber is silica-

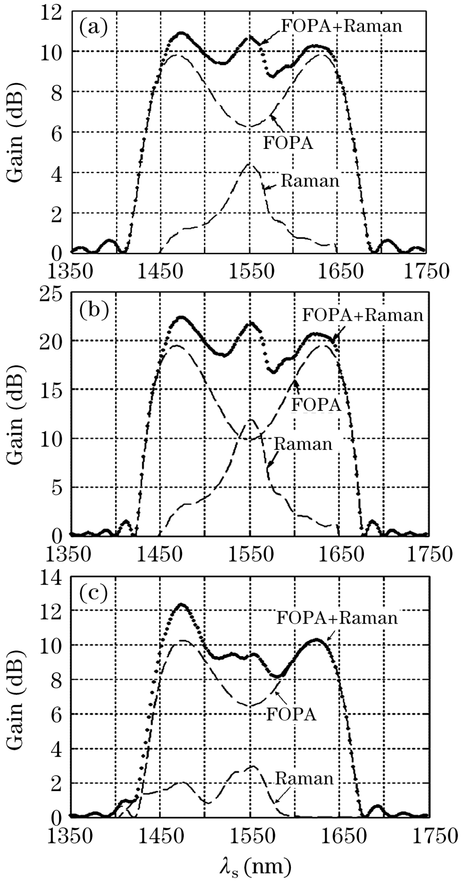

Fig. 2. Gain spectra of R-FOPA made with silica/telluride-based fiber, one forward parametric pump, and one backward Raman pump. Parameters refer to Table 1. (a) No. (1), (b) No. (5), (c) No. (7).

Table 1. Optimization Parameters in R-FOPA

No.	Optimal Object	Preset Parameter			Optimized Parameter		
	(on-off	k	γ	$\lambda_{\mathrm{p-Raman}}$	OPA	Raman	L
	Gain/Bandwidth)	($\times 10^4$)	($\mathrm{W}^{-1}\cdot\mathrm{km}^{-1}$)	$\lambda_2/\lambda_3/\lambda_4$ (nm)	P_1 (W)	$P_2/P_3/P_4$ (W)	(m)
One OPA Pump, One Raman Pump, Silica Fiber							
(1)	10 dB / 200 nm	4.7	18	1450	2.338	6.696	43
(2)	10 dB / 200 nm	4.7	11	1450	3.816	6.669	43
(3)	10 dB / 200 nm	8.6	18	1450	4.660	13.333	21
(4)	10 dB / 200 nm	8.6	11	1450	7.572	13.192	22
(5)	20 dB / 200 nm	4.7	18	1450	2.333	11.109	70
(6)	20 dB / 200 nm	4.7	11	1450	3.816	11.116	70
One OPA Pump, One Raman Pump, Telluride Fiber							
(7)	10 dB / 200 nm	4.7	18	1380	1.943	0.234	53
One OPA Pump, Two Raman Pumps, Telluride Fiber							
(8)	10 dB / 200 nm	4.7	18	1380/1430	3.889	0.317/0.444	25
(9)	10 dB / 200 nm	4.7	18	1390/1440	3.651	0.476/0.508	25
(10)	10 dB / 200 nm	4.7	18	1400/1450	2.857	0.444/0.349	32
One OPA Pump, Three Raman Pumps, Telluride Fiber							
(11)	10 dB / 200 nm	4.7	18	1500/1390/1350	2.187	0.484/0.203/0.306	40
(12)	20 dB / 200 nm	4.7	18	1500/1390/1350	2.032	0.716/0.310/0.442	67

based. We expect to achieve a 200-nm bandwidth spectrum (1450 − 1650 nm) of either a 10-dB gain with ripple of less than 2 dB or a 20-dB gain with ripple of less than 4 dB. $\lambda_{\mathrm{P-FOPA}} = 1550$ nm and $\lambda_{\mathrm{P-Raman}} = 1450$ nm. $k = 4.7 \times 10^4$ or 8.6×10^4 s/m^4, $\gamma = 18$ or 11 W$^{-1}\cdot$km^{-1}. The parametric pump power, Raman pump power and fiber length are optimized by GA. Six sets of optimized results are obtained as listed as No. (1) − (6) in Table 1. Figures 2(a) and (b) show the corresponding gain spectra of No. (1) and (5). We find that high-power Raman pumps are required for the R-FOPA hybrid amplifier to reach the expected on/off gain. Moreover, though the composite gain profiles are flatter than a single one-pump FOPA or FRA, the gain curve still has much room to be further equalized.

We then replace the silica fiber with telluride-based one and set $\lambda_{\mathrm{P-Raman}} = 1380$ nm. GA gets the optimal parameter values for a 10-dB gain spectrum of 200-nm bandwidth as listed as No. (7) in Table 1 and shown in Fig. 2(c). As we can see, Telluride fiber's twin-peaked Raman gain spectrum leads to an even larger gain imbalance, however, its high g_{Raman} allows much lower pump powers. We then increase the number of Raman pumps at different wavelengths to equalize the gain profile, while keeping the advantage of telluride fiber's large g_{Raman}. For the configuration using two Raman pumps, the optimal parameter values for a 200-nm bandwidth spectrum of 10-dB gain are listed as No. (8) − (10) in Table 1. The corresponding gain profiles are displayed in Fig. 3. For the configuration using three Raman pumps, the optimal parameter values for a 200-nm bandwidth spectrum of 10-dB or 20-dB gain are listed as No. (11) and (12) in Table 1. Figure 4 shows the corresponding gain profiles. As we can see, with more Raman pumps, the telluride fiber-based hybrid R-FOPA can achieve a flatter gain profile pumped by lower powers. For a telluride-based R-FOPA powered by one forward parametric pump and three backward Ramn pumps, it can achieve a 200-nm bandwidth spectrum with the gain of 10 dB and ripple of less than 2 dB in the wavelength region of 1450 − 1650 nm (Fig. 4(a)), or a 200-nm bandwidth spectrum with the gain of 20 dB and ripple of less than 4 dB in the wavelength region of 1450 − 1650 nm (Fig. 4(b)). The forward parametric pump ($\lambda_{\mathrm{P-FOPA}} = 1550$ nm) forms the main gain spectrum, and the backward Raman pumps ($\lambda_{\mathrm{P-Raman}} = 1500$, 1390 and 1350 nm) compensates for the gain imbalance.

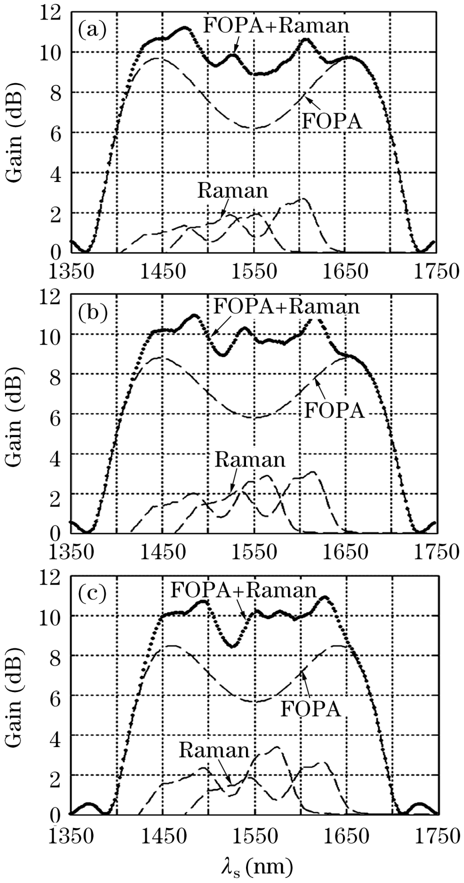

Fig. 3. Gain spectra of R-FOPA made with telluride-based fiber, one forward parametric pump, and two backward Raman pumps. Parameters refer to Table 1. (a) No. (8), (b) No. (9), (c) No. (10).

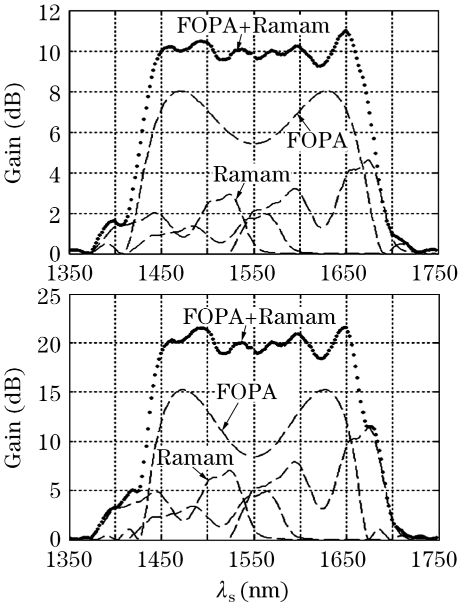

Fig. 4. Gain spectra of R-FOPA made with telluride-based fiber, one forward parametric pump, and three backward Raman pumps. Parameters refer to Table 1. (a) No. (11), (b) No. (12).

The hybrid R-FOPA amplifier proposed here has pratical applicability. To fully utilize its potential bandwidth in a WDM system, the signal interleaving method could be used. Passing through an interleaver, all the input signals are separated into two groups to be amplified by two independent FOPAs, and then combined by a broadband coupler when the idlers are filtered. However, some potential problems need to be solved, including polarization alignment, ZDW variation, and pump-pump interaction.

In conclusion, GA scheme is extended to effectively optimize the pump powers and the fiber length. The optimization results indicate that R-FOPA, with a telluride-based fiber of 67 m in length pumped by one forward parametric pump and three backward FRA pumps, can provide a 200-nm flat bandwidth spectrum with the gain of 20 dB and ripple of less than 4 dB.

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