Evolution of modes in double-clad Raman fiber amplifier

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Stimulated Raman scattering in a double cladding optical fiber is studied with a continuous wave laser used as a pump source. Under various launch conditions, pump modes are differently excited. Considering the mode coupling effect among the pump modes, the evolution of the power in the Stokes modes is studied. The results show that the scattered waves (the Stokes waves) in the fiber core with 9-μm diameter and 0.14 NA could propagate predominantly in the fundamental mode of the fiber by carefully adjusting the pump light launching conditions.

Keywords: fiber nonlinear optics, high power Raman fiber amplifier, fiber mode

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1. Introduction

Raman scattering is an inelastic nonlinear effect arising from the interaction between incident light and the vibrational states of material. Owing to Raman scattering, a pump photon is scattered into a longer wavelength photon accompanied with the generation of an optical phonon in the medium. Generally, inelastic scattering to longer wavelengths is called Stokes scattering. The first observation of spontaneous Raman scattering dates from 1928.[1] The first Raman fiber amplifier (RFA) was demonstrated by Stolen and Ippen in 1973.[2] In 2002, a cladding pumped (CP) RFA was proposed and demonstrated by Nilsson *et al*. for the first time.[3]

Stimulated Raman scattering (SRS) is a nearly instantaneous process. Therefore, the signal and pump beams must overlap with each other to amplify the signal through SRS.[4,5] Most research has concentrated on Raman amplification in a single-cladding fiber[6,7] and photonic crystal fiber,[8,9] while there has only been a little on SRS in DC (double-cladding) Raman fiber. Ji *et al*.[10] have modeled the mode evolution in the DC Raman fiber amplifier; they regarded two signal core modes as LP_{01} and LP_{02} modes. However, there are only two signal core modes in the DC Raman fiber, which should be the LP_{01} and LP_{11} modes, as concerned in our paper. Here we consider the effect of mode coupling on the mode evolution in the DC Raman fiber amplifier, which was not considered in Ref. [10]. The aim of this paper is to theoretically investigate SRS in double-cladding Raman fiber whose core can support a few modes; also, to determine the evolutions of the power in the Stokes modes for different pump excitations. The results show that SRS preferentially selects the fundamental mode at the Stokes wavelength, especially when the pump light is excited in only a few lower-order modes.

2. SRS in optical fiber

The model of an end-pumped double-clad Raman fiber amplifier is described schematically in Fig. 1. Both pump and signal beam are assumed to propagate in the positive direction of the coordinate z along the fiber. The linewidths of the pump source and of the seed laser are wide enough to suppress the stimulated Brillouin scattering (SBS), so the SBS is ignored, just as in Ref. [10].

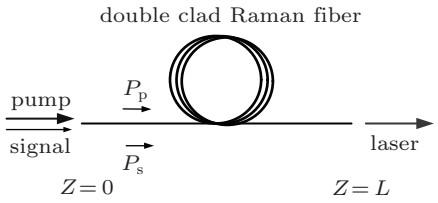


Fig. 1. Schematic illustration of the end-pumped fiber amplifier.

The following two coupled equations describe the evolutions of the pump and Stokes (i.e. signal) intensity through the SRS process along the single mode fiber (SMF) in the CW or quasi-CW regime:[11]

$$\frac{\mathrm{d}I_\mathrm{s}}{\mathrm{d}z} = g_\mathrm{R} I_\mathrm{p} I_\mathrm{s} - \alpha_\mathrm{s} I_\mathrm{s}, \tag{1}$$

$$\frac{\mathrm{d}I_\mathrm{p}}{\mathrm{d}z} = -\frac{\omega_\mathrm{p}}{\omega_\mathrm{s}} g_\mathrm{R} I_\mathrm{p} I_\mathrm{s} - \alpha_\mathrm{p} I_\mathrm{p}, \tag{2}$$

where, the variables I_i, ω_i and α_i represent the intensity, frequency and propagation loss respectively, with subscripts $i = \mathrm{p}, \mathrm{s}$ denoting the pump and Stokes beams; g_R is the Raman gain coefficient.

In the double cladding fiber (DCF), the coupled equations are similar but more complicated than those in the SMF. The pump and signal beams propagate within several modes in the inner cladding and the core of the DCF, respectively. The local Raman gain is proportional to the local intensities of the pump

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and the signal. The modes of both pump and signal each have a unique power distribution in the cross section of the fiber. Accordingly, it is necessary to consider all modes involved in the SRS process. In the CW or quasi-CW regime, the intensity evolutions of each propagating mode at different wavelengths in Raman scattering can be modified from Eqs. (1) and (2). For CP Raman fiber devices, it is desired that almost all the pump light can be converted into the 1st Stokes, whereas the 2nd or higher order Stokes is not excited. However, the high order Stokes are always inevitable in ordinary CP Raman fiber amplifiers. In this paper, only the 1st and 2nd Stokes light, together with the pump light are considered. Moreover, the mode coupling among the pump modes is also considered in the model. Through integration across the transverse section, we can obtain the coupled equations as follows:

$$\begin{aligned}\frac{\mathrm{d}P(z,\lambda_0,l)}{\mathrm{d}z} &= -\alpha(\lambda_0,l)P(z,\lambda_0,l) - P(z,\lambda_0,l)\frac{\lambda_1}{\lambda_0} \\ &\quad \times \sum_{m=1}^{N_1}\left(P(z,\lambda_1,m)\frac{g_{\mathrm{R}}(\lambda_0,\lambda_1)}{A_{\mathrm{eff}}(\lambda_0,\lambda_1,l,m)}\right) \\ &\quad - \sum_{k=1}^{N_0} d_{l0}[P(z,\lambda_0,l) - P(z,\lambda_0,k)], \qquad (3)\\ \frac{\mathrm{d}P(z,\lambda_1,m)}{\mathrm{d}z} &= -\alpha(\lambda_1,m)P(z,\lambda_1,m) + P(z,\lambda_1,m) \\ &\quad \times \sum_{l=1}^{N_0}\left(P(z,\lambda_0,l)\frac{g_{\mathrm{R}}(\lambda_0,\lambda_1)}{A_{\mathrm{eff}}(\lambda_0,\lambda_1,l,m)}\right) \\ &\quad - P(z,\lambda_1,m)\frac{\lambda_2}{\lambda_1} \\ &\quad \times \sum_{n=1}^{N_2}\left(P(z,\lambda_2,n)\frac{g_{\mathrm{R}}(\lambda_1,\lambda_2)}{A_{\mathrm{eff}}(\lambda_1,\lambda_2,m,n)}\right), \qquad (4)\\ \frac{\mathrm{d}P(z,\lambda_2,n)}{\mathrm{d}z} &= -\alpha(\lambda_2,n)P(z,\lambda_2,n) + P(z,\lambda_2,n) \\ &\quad \times \sum_{m=1}^{N_1}\left(P(z,\lambda_1,m)\frac{g_{\mathrm{R}}(\lambda_1,\lambda_2)}{A_{\mathrm{eff}}(\lambda_1,\lambda_2,m,n)}\right), \qquad (5)\end{aligned}$$

where the variable $P(z,\lambda_i,l)$ represents the power of the mode l with the wavelength λ_i at the distance z. The subscript index i denotes the pump ($i=0$), 1st Stokes ($i=1$) and 2nd Stokes ($i=2$). The Raman gain coefficient $g_{\mathrm{R}}(\lambda_i,\lambda_j)$, corresponding to the pump wavelength λ_i and the signal wavelength λ_j, is determined by the material distribution and composition inside the transverse section. The variable $\alpha(\lambda_i,l)$ is referred to as the background loss at wavelength λ_i with mode l. The background loss is assumed not to vary along the fiber. Finally, N_j is the number of modes that can be supported at the wavelength λ_j inside the fiber. d_{l0} is the power coupling coefficient between the modes of the pump light. The overlap value $A_{\mathrm{eff}}^{-1}(\lambda_i,\lambda_j,l,k)$ corresponding to the interacting pump wavelength λ_i and signal wavelength λ_j with specific mode l and k respectively, is given by

$$\begin{aligned}(A_{\mathrm{eff}})^{-1} &= \frac{\iint I_{\mathrm{p}} I_{\mathrm{s}}\,\mathrm{d}S}{\iint I_{\mathrm{p}}\,\mathrm{d}S \iint I_{\mathrm{s}}\,\mathrm{d}S} \\ &= \frac{\iint |F_{\mathrm{p}}(x,y)|^2 |F_{\mathrm{s}}(x,y)|^2\,\mathrm{d}S}{\iint |F_{\mathrm{p}}(x,y)|^2\,\mathrm{d}S \iint |F_{\mathrm{s}}(x,y)|^2\,\mathrm{d}S}, \qquad (6)\end{aligned}$$

where the variable $F_i(x,y)$ is the transverse mode field distribution with subscripts $i = \mathrm{p},\mathrm{s}$ denoting the pump and Stokes beams.

3. Mode excitation

The overlap between pump and signal beams is important since SRS is nearly an instantaneous process. Furthermore, the pump light propagates in a lot of modes in the inner cladding. The transverse power distribution of the pump primarily determines the Raman gain profile in a transverse section, thus determining which Stokes-mode can be amplified through SRS. So it is very important to take into consideration the transverse power distribution of the pump and signal beams.

In the absence of mode coupling, the power of each pump mode is determined by the modes excited at the launch end, accompanied with the depletion of an individual mode. The modal excitation depends on the launch conditions, such as spot size, offset and incident angle of the incident pump beam.[12] In practice, the modal power distribution is very complicated to measure in fiber.[13]

According to the mode matching method, the excitation coefficient $\eta_{m,n}$ of the mode $F_{m,n}(x,y)$, where m and n are the azimuthal number and the radial mode number respectively for an incident input field, $F_i(x,y)$ is calculated as follows:[14]

$$\begin{aligned}&\eta_{m,n} \\ &= \frac{\int_{-\infty}^{+\infty}\int_{-\infty}^{+\infty} F_i(x,y)F_{m,n}(x,y)\,\mathrm{d}x\mathrm{d}y}{\sqrt{\int_{-\infty}^{+\infty}\int_{-\infty}^{+\infty}|F_i(x,y)|^2\,\mathrm{d}x\mathrm{d}y\int_{-\infty}^{+\infty}\int_{-\infty}^{+\infty}|F_{m,n}(x,y)|^2\,\mathrm{d}x\mathrm{d}y}}, \qquad (7)\end{aligned}$$

where x and y are transverse orthogonal coordinates.

When the pump source has a poor beam quality, all pump modes may be equally excited. However, if the pump source has a better beam quality, it will only excite a subset of the pump modes, and the Raman conversion will vary accordingly. In particular, lower order modes can then be selected and excited on purpose in the conditions of appropriate launching.[15]

4. Numerical simulation results and discussion

4.1. Parameters used for simulations

We use Eqs. (4)–(6) to simulate a single-stage CP RFA. The amplifier consists of a DCRF with 9-μm core diameter and 21.6-μm inner-cladding diameter, as utilized in Ref. [10]. The area ratio between the inner cladding and the core is less

than 8, which is required in the DC RFA. It is assumed that the refraction indices of the core, inner-cladding and outer-cladding are 1.4667, 1.46, and 1.4433, respectively. The values of background loss are 3.1 dB/km and 2.3 dB/km in the core and the inner cladding respectively. The Raman gain coefficients are 5.29×10^{-14} m/W and 6.34×10^{-14} m/W in the inner cladding and core, respectively. The Raman fiber design is representative of high power Raman fiber amplifiers; it also allows efficient modeling. Theoretically, the model in this paper is suitable for all kinds of DCRFs.

Based on the refractive index profile (RIP) of the DCRF mentioned above, the effective indices are calculated for different modes at different wavelengths. At 1070 nm, there are 31 linearly polarized (LP) fiber modes in the inner cladding: two of them are core modes, the others are cladding modes. These modes are split into two or four modes if polarization degeneration and sine and cosine modes are considered. At 1120 nm and 1180 nm, there are two linearly polarized (LP) core modes, namely LP_{01} and LP_{11}. The effective indices of all modes at 1070 nm are shown in Fig. 2.

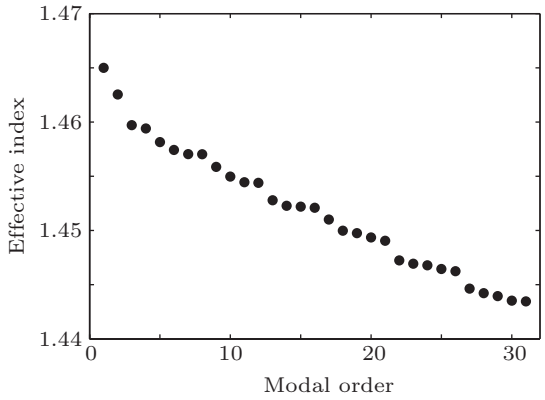


Fig. 2. Effective indices of modes at 1070 nm in the DCRF.

The overlap values between various modes at the pump wavelength and modes at Stokes wavelength are calculated according to Eq. (4). Figures 3(a) and 3(b) show the overlap values between each mode at 1070 nm and LP_{01}, LP_{11} modes at 1120 nm, respectively. The results show that the LP_{01} mode at 1120 nm has a larger overlap value with the pump modes than the LP_{11} mode.

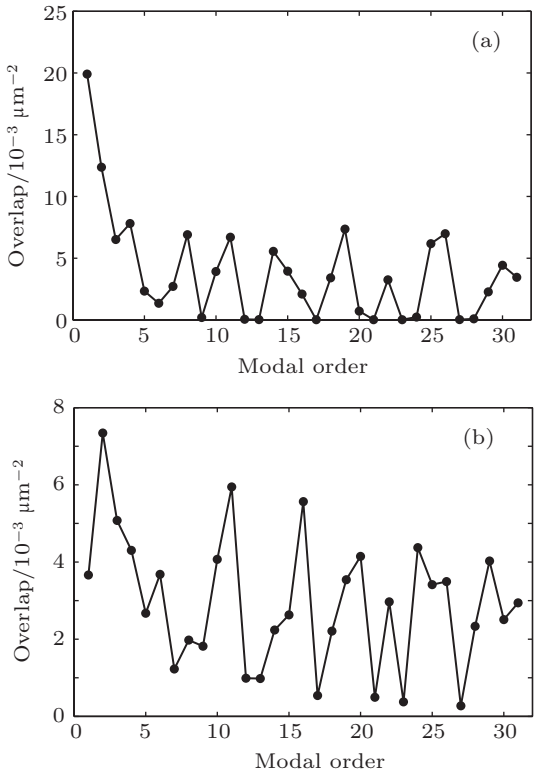


Fig. 3. Overlaps between each mode at 1070 nm and (a) LP_{01} mode at 1120 nm; (b) LP_{11} mode at 1120 nm.

4.2. Pump modes equally excited

In our simulation, all pump modes are assumed to be equally excited and two core modes of the 1st Stokes seed light are assumed to be equally excited at the input, so as to examine whether the fundamental mode can be amplified more easily and extract more pump power than high-order modes, Note that the mode coupling is not taken into account here. The fiber in the simulation is short enough to ignore the walk-off effect in this case. A 50-mW LP_{01} mode and a 50-mW LP_{11} mode at 1120-nm together with 2850-W pump light at 1070 nm are launched into the DCRF from one end.

By using the overlaps and initial conditions given above, the SRS process can be numerically simulated by Eqs. (3)–(5). The input and output powers of the pump modes are shown in Table 1.

Table 1. Input and output powers of the equally excited pump modes at 1070 nm.

Mode	LP_{01}	LP_{11}	LP_{21}	LP_{02}	L_{P12}	LP_{31}	LP_{22}	LP_{03}
Input power/W	50	100	100	50	100	100	100	50
Output power/W	0	0	0.02	0	3.39	5.71	4.36	0.03
Mode	LP_{41}	LP_{32}	LP_{13}	LP_{51}	LP_{61}	LP_{04}	LP_{23}	LP_{42}
Input power/W	100	100	100	100	100	50	100	100
Output power/W	37.76	0.41	0.01	61.49	63.18	0.09	0.73	1.26
Mode	LP_{71}	LP_{33}	LP_{14}	LP_{52}	LP_{81}	LP_{43}	LP_{91}	LP_{62}
Input power/W	100	100	100	100	100	100	100	100
Output power/W	76.44	1.48	0.02	8.57	77.89	1.25	81.77	12.36
Mode	LP_{24}	LP_{05}	LP_{101}	LP_{72}	LP_{53}	LP_{15}	LP_{34}	
Input power/W	100	50	100	100	100	100	100	
Output power/W	0.06	0.014	85.2	33.66	2.05	0.49	1.05	

The powers distributed over the various modes of 1st Stokes and 2nd Stokes along the fiber longitudinal direction are given in Fig. 4.

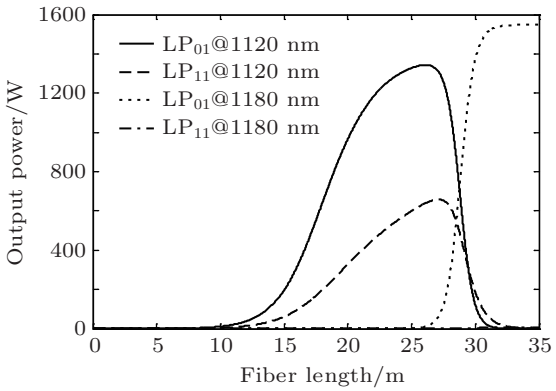


Fig. 4. Power distribution of the Stokes modes when pump modes are equally excited.

First of all, we can see that the pump powers in almost all modes except the LP_{i1} modes ($i = 4, 5, \ldots, 10$) are effectively converted into the 1st Stokes mode, despite the variation in overlap between different pump modes and the Stokes modes. Because the LP_{i1} modes ($i = 4, 5, \ldots, 10$) have little power distributed in the core, the overlap with the Stokes core modes is very small.

Besides, if the fiber length is suitably chosen to be, for example, 27 m, a high conversion efficiency of 1st Stokes in such a device will be achieved. The conversion efficiency from pump to 1st Stokes light at this optimum length is 87.4% with consideration of the residual pump power, which is comparable to the efficiency of the YDFL. The output power of 1st Stokes is 1980 W, of which 67.7% is in LP_{01} mode. However, extending the fiber length to 32 m, the 2nd Stokes light will be dominant in the output; it is interesting that almost all of the output light beams are in the LP_{01} mode. The conversion efficiency from pump to 2nd Stokes light at this length is 68.1% with considering the residual pump power. To sum up, the output of RFA is quite sensitive to the Raman fiber length and the 1st Stokes power is limited by the 2nd Stokes generation. So it is more significant to control the gain fiber length within different pump powers of RFA than to control the rare earth doping fiber laser. The model in this paper can be used to determine the optimum Raman fiber length of RFA within various amounts of pump power.

Furthermore, the LP_{01} mode sees higher Raman gain at the 1st Stokes than the LP_{11} mode, which transfers most of the pump power along the fiber. Therefore, at the output, the signal beam is nearly diffraction limited. The key reason why most of the pump power is Raman-scattered into the LP_{01} mode is that the LP_{01} mode has a larger overlap value with the pump modes than the LP_{11} mode. In addition, the higher Raman gain coefficient in the core area favors the generation of the core-modes. Moreover, the light in the 2nd Stokes is mostly in the LP_{01} mode. The simulations suggest that this Raman fiber can preferentially select the fundamental mode at the Stokes wavelength especially at the high order Stokes wavelength.

The mode coupling in multimode fiber is a very complex problem which is caused by many factors,[12] including an internal flaw generated during the fabrication of the fiber and other external disturbances, such as bending, twisting, etc. The pump light trapped by the inner cladding is in heavily multimode, so the mode coupling effect between the pump modes is considered. The coupling coefficient between the nonadjacent modes is much smaller than that between the adjacent modes, so it can be neglected. In order to exhibit our model that has the ability to process this case, we give a simple example to reveal the mode coupling effect among the closest modes. Suppose that the coupling coefficient between the adjacent modes of the pump light is 0.01 m^{-1} (the value is from Ref. [10]), when the fiber length is well chosen, the maximum output power of 1st Stokes is 1990 W, of which 70.1% is in the LP_{01} mode. Compared with the case without considering the mode coupling, much pump power is converted into 1st Stokes; the ratio of the LP_{01} to the 1st Stokes is also improved in this case. This results from the fact that some pump modes, which are not largely converted into the 1st Stokes, are coupled into modes that can be heavily depleted by the 1st Stokes. However, the effect of the mode coupling on the output characteristics is slight. As a result, we conclude that the mode coupling between the pump modes can be neglected in the simulation.

The simulation presented here shows theoretically that a DCRF can work efficiently as a CP Raman converter and transfer power into the diffraction limited signal from a multimode pump source. The double cladding Raman amplifier can act as a fiber laser configuration with high power and good beam quality.

4.3. Pump modes unequally excited

When all pump modes are assumed to be equally excited, pump modes such as LP_{41} and LP_{51} cannot effectively transfer energy into the 1st Stokes. These modes can be less excited by adjusting the pump launch condition, on the assumption that the pump beam quality is good enough for selective pump-mode excitation. The conversion efficiency can be further improved in this case.

We suppose that the incident pump is a diffraction-limited Gaussian beam with a 24-μm beam width centered at a 3° incident angle. The pump modal decomposition used in this simulation is given in Table 2.[10]

Table 2. Power ratios of the excited pump modes at 1070 nm.

Mode	LP_{01}	LP_{11}	LP_{21}	LP_{02}	LP_{12}	LP_{31}	LP_{22}	LP_{32}	LP_{13}
Power ratio/%	31.9	21.0	5.1	4.6	23.9	0.7	4.5	1.5	6.7

The 1-kW pump beam at 1070 nm with 50-mW LP_{01} mode and 1-kW pump beam at 1120 nm with 50-mW LP_{11} mode are launched into the fiber from the same end. The mode coupling effect is not taken into account for the reason mentioned in the previous section. Utilizing the overlaps and pump power distribution given above, the SRS process can be numerically simulated by Eqs. (4)–(6). The input and output power of the pump modes are shown in Table 3.

Table 3. Input and output powers of the unequally excited pump modes at 1070 nm.

Mode	LP_{01}	LP_{11}	LP_{21}	LP_{02}	LP_{12}	LP_{31}	LP_{22}	LP_{32}	LP_{13}
Input power/W	319	210	51	46	239	7	45	15	67
Output power/W	0	0	0.06	0.01	22.18	1.81	2.87	0.27	0.08

The powers distributed over the various modes of 1st Stokes and 2nd Stokes along the fiber longitudinal direction are given in Fig. 5.

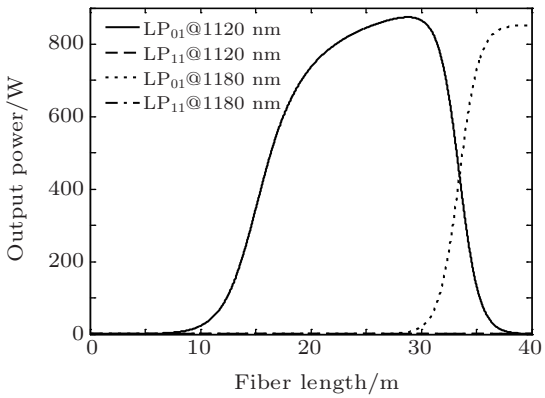


Fig. 5. Power distributions of the Stokes modes when pump modes are unequally excited.

As illustrated in Fig. 5, the highest conversion efficiency to 1st Stokes in such a device is 90.9% with consideration of the residual pump power if the fiber length is 29 m. What is more, the LP_{01} mode sees approximately all Raman gains at the 1st Stokes. The reason is that the LP_{01} mode has a much larger overlap value with the excited pump modes than the LP_{11} mode. Therefore, the signal beam is diffraction-limited at the output in this case, thus concluding that the beam quality of the 1st Stokes is greatly improved compared with that in the case of the pump beam. The simulation suggests that lower order pump modes overlap well with core modes especially the LP_{01} mode at the signal wavelength. To sum up, a pump source with only a few lower order pump modes benefits the mode selection of the signal in RFA. This conclusion is consistent with the research result in Ref. [10].

5. Conclusion

In this paper, we investigate the SRS in double-cladding Raman fiber whose core supports two modes and study the behaviors of the power in the Stokes mode that are due to different pump excitations. The results show that the SRS preferentially selects the fundamental mode at the Stokes wavelength, especially when the pump light excites only a few lower-order modes under appropriate launching conditions. A multimode source with sufficiently high power can be Raman-converted into a single-mode beam in a double-clad fiber having been configured as a Raman amplifier. The model in this paper can be used to design the Raman fiber for a high power DC RFA with good quality.

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