Instruction manual for LAPAREX

1 Introduction

Determination of device parameters in distributed feedback (DFB) lasers is very important for optimization of laser characteristics and system design. Although the coupling coefficient is the most important parameter, its determination has only been possible in AR-coated index-coupled DFB lasers. Moreover, this is not an easy task or not very accurate if there are facet reflectivities remaining. And although phacet phase of the grating also gives influence on laser performance, it is uncontrollable and very difficult to measure. In this LAser PARameter EXtraction program (LAPAREX), parameters are derived by numerical fitting of subthreshold spectrum. Using this way, not only index coupling coefficient κ_i, but also gain coupling coefficient κ_g, gain profile $g = g_1 - g_2(E - E_p)^2$, both facet phase $\theta_{front}, \theta_{rear}$, refractive index n_{eff} and it's wavelength dispersion $dn/d\lambda$ can be determined. Moreover, AR coating doesn't needed.

2 Theorem

See another explanation paper.

3 Preparation

You get the following executable file

For Window version

```
anlyser.exe   autofs.exe   autos.exe    fitting.exe   initpar.exe
autofi.exe    autoi.exe    extract.exe  fspec.exe     spectrum.exe
```

For Macintosh version

```
anlyser.exe   autofs.exe   autos.exe    fitting.exe   mactrans.exe
autofi.exe    autoi.exe    execution    fspec.exe     spectrum.exe
```

and following example file

```
anlyser.bat     example0.spe    example2.spe    example4.spe    example6.spe
ex8.err         example1.dat    example3.dat    example5.dat    example7.dat
ex8.par         example1.err    example3.err    example5.err    example7.err
ex8.spe         example1.par    example3.par    example5.par    example7.par
example.bat     example1.spe    example3.spe    example5.spe    example7.spe
example0.dat    example2.dat    example4.dat    example6.dat    example8.dat
example0.err    example2.err    example4.err    example6.err    example8.par
example0.par    example2.par    example4.par    example6.par    example8.spe
```

'example0.dat' is measured spectrum of IC-DFB laser, 'example1 $\sim$ 9.dat' is measured spectrum of the same GC-DFB laser. 'example1 $\sim$ 4' is from right facet, and 'example5 $\sim$ 8' is from left facet with changing injection current from 16 [mA] to 22 [mA] by 2 [mA] step.

'*.dat' is measured spectrum data, '*.par' is *correct* extracted parameters, and '*.spe' is *correct* fitted spectrum.

4 Execution program

command	input file	output file	function
`spectrum.exe`	`spec.dat`, `mydfb.dat`	`spec.new`	calculate spectrum
`fspec.exe`	`spec.dat`, `dfb.new`	`fspec.new`	calculate spectrum
`initpar`	`spec.dat`	`fspec.new`,`dfb.new`, (`peak.new`)	calculate initialized parameter for fitting
`extract`	`spec.dat`	`fspec.new`,`dfb.new`, (`peak.new`)	parameter extraction by fitting
`fitting.exe`	`spec.dat`, `dfb.new`$^{\circ}$	`dfb.new`	parameter extraction by fitting (appropriate initialized parameters should be given)
`anlyser.exe`	`errspec.dat`, `errparam.dat`	`err.new`	error estimation

caution : Files with $\circ$ are removed after execution.

There are some other executable program and input/output files, but you don't need to know their detail.

5 How to execute

For Windows version, this program can run only on "DOS Window on Windows95", cannot run on MS-DOS. And all the command are executed by the command line.

For Macintosh version, you should edit the file "`command`", and write command in this file, like "`extract ICDFB 350 0.240`". Then double clic on the icon "`execution`". You can use only following 6 command `fspec.exe, spectrum.exe, anlyser.exe, copy, extract, initpar`. And `fspec.exe, spectrum.exe, anlyser.exe, fitting.exe` can be also executed by double clic on the icon itself.

For Windows version, you can make batch files and you don't have to be in front of the computer. But for Macintosh version, execution program request "push RETURN to continue" so often that you have to be in front of the computer even though you can make batch files.

6 Simple use

In most cases, this simple way is enough to extract parameters.

1. Copy the measured spectrum file to `spec.dat`.
2. When the laser is as-cleaved, input the command

   `extract` *code cavitylength(μm) gratingpitch(μm)*

   when you want to specify the facet power reflectivity, like AR-HR coated lasers, input the command

   `extract` *code cavitylength(μm) gratingpitch(μm)* `-r` *Rrear(%) Rfront(%)*

   default facet power reflectivity is calculated by $R = (\frac{n-1}{n+1})^2$.
3. Wait untill calculation is over. (in a few minutes)
4. Extracted parameters are written in the file `dfb.new`, and fitted spectrum are written in the file `fspec.new`.
5. Display `spec.dat` and `fspec.new` in the same graph to confirm the fitting was succeeded.
6. Open the file `dfb.new` to see the value of extracted parameters.

If you want to estimate error of extracted parameters, follow next step.

7. Copy `dfb.new` to `errparam.dat`.
8. Copy `spec.dat` to `errspec.dat`.
9. Execute

```
anlyser.exe
```

10. — coffee break — (in a few *hour*)
11. Open the file `err.new` to see the value of extracted parameters.

Meanings of input/output files are written in section 8.

7 Example

7.1 Example No.0

Known information • as cleaved IC-DFB. • first order grating and $\Lambda = 240$[nm]. • $L = 350[\mu m]$

1. Copy `example0.dat` to `spec.dat`.
2. Execute

```
extract ICDFB 350 0.240
```

3. Wait untill calculation is over. (in a few minutes)
4. Display `spec.dat` and `fspec.new` in the same graph to confirm the fitting was succeeded.
5. Open the file `dfb.new` to see the value of extracted parameters. `example0.par` and `example0.spe` is the *correct* parameters and spectrum.
6. Copy `dfb.new` to `errparam.dat`.
7. Copy `example0.dat` (`spec.dat`) to `errspec.dat`.
8. Execute

```
anlyser.exe
```

9. — coffee break — (in a few *hour*)
10. Open the file `err.new` to see the value of extracted parameters. `example0.err` is the *correct* error region.

7.2 Example No.4

Known information • as cleaved GC-DFB. • first order grating and $\Lambda = 0.23693$[nm]. • $L = 550[\mu m]$

1. Copy `example4.dat` into `spec.dat`.
2. Execute

```
extract GCDFB 550 0.23693
```

3. Wait untill calculation is over. (in a few minutes)
4. Display `spec.dat` and `fspec.new` in the same graph to confirm the fitting was succeeded.
5. Open the file `dfb.new` to see the value of extracted parameters. `example4.par` and `example4.spe` is the *correct* parameters and spectrum.

6. Copy `dfb.new` to `errparam.dat`.
7. Copy `example4.dat` (`spec.dat`) to `errspec.dat`.
8. Execute

   `anlyser.exe`

9. — coffee break — (in a few *hour*)
10. Open the file `err.new` to see the value of extracted parameters. `example4.err` is the *correct* error region.

8 Format and meanings of input/output files

8.1 mydfb.dat, dfb.new

Meaning of parameters are as follows.

line 1 Code. `ICDFB` or `GCDFB`

line 2 Order of the grating. This program can cope with only when this parameter is `1`.

line 3 L : Cavity length.

line 4 Λ : Grating pitch.

line 5 κ_i : Index coupling coefficient.

line 6 κ_g : Gain coupling coefficient.

line 7 g_1 : Net peak gain*.

line 8 g_2 : Net gain curvature*.

line 9 λ_p : Wavelength in which gain is maximum*.

line 10 J_0 : Parameter to move spectrum up and down without changing the shape of the spectrum.

line 11 n_{Bragg} : Refractive index at Bragg wavelength*.

line 12 $dn/d\lambda$: Wavelength dispersion of refractive index*.

line 13 R_{rear} : Power reflectivity on rear facet.

line 14 R_{front} : Power reflectivity on front facet.

line 15 θ_{rear} : Phase of the grating on rear facet$^\triangleright$.

line 16 θ_{front} : Phase of the grating on front facet$^\triangleright$.

line 17 This parameter stands for whether spectrum is measured in log scale ([dB]) or linear scale ([mW]). Spectrum should be measured with log scale, that is, this parameter should be `1`.

line 18 This parameter stands for whether these program calculate spectrum around bragg wavelength or around measured wavelength in `spec.dat`. When `1`, at the wavelength in `spec.dat`, and when `0`, around bragg wavelength.

line 19 Goodness-of-fit. This line exists only on Windows version. "sigma2" means σ^2 defined as follows,

$$\sigma^2 \equiv \frac{1}{N}\sum_i^N \{y_m(\lambda_i) - y_c(\lambda_i; \boldsymbol{a}_{fit(0)})\}^2 \tag{1}$$

and "max round trip gain" means the maximum value of the round trip gain at any position and any wavelength. "sigma2" is desired to be close to 0, and "max round trip gain" should be less than 1. (This line doesn't exist in Macintosh version)

* The model of gain profile $g(\lambda)$ is

$$\begin{aligned} g &= \Gamma\{g_{a1} - g_{a2}(E - E_p)^2\} - \Gamma\alpha_{active} - (1-\Gamma)\alpha_{clad} && (2)\\ &= \underline{\underline{\Gamma g_{a1} - \alpha}} - \underline{\underline{\Gamma g_{a2}}}(E - E_p)^2 && (3)\\ &= \underline{\underline{g_1}} - \underline{\underline{g_2}}(E - E_p)^2 && (4)\\ & && (5) \end{aligned}$$

where

$$E_p = \frac{hc}{q\lambda_p} \tag{6}$$

⋆ The model of refractive index $n(\lambda)$ is

$$n_{eff} = n_{Bragg} + \frac{dn}{d\lambda}(\lambda - \lambda_{Bragg}) \tag{7}$$

▷ The definition of facet phase is,

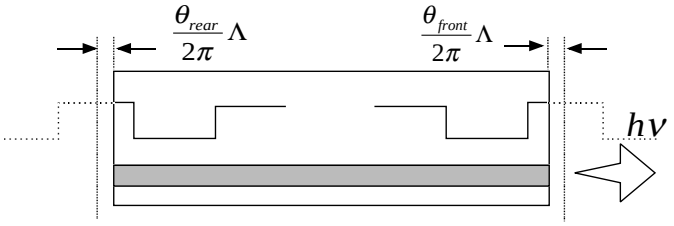

図 1: definition of the facet phase

then, we can represent

$$\begin{aligned} n(z) &= n + (\Delta n)\cos(2\pi z/\Lambda + \theta_{rear}) && (8)\\ g(z) &= g + (\Delta g)\cos(2\pi z/\Lambda + \theta_{rear}) && (9) \end{aligned}$$

so, κ_i is always positive, and κ_g is positive when "in-phase", and κ_g is negative when "anti-phase". And cavity length become

$$L = m\Lambda - \frac{\theta_{rear}}{2\pi}\Lambda - \frac{\theta_{front}}{2\pi}\Lambda \tag{10}$$

`0` or `1` beside each parameter means flag for fitting. When `0`, the value is fixed. When `1`, the parameter is fitted.

8.2 spec.dat, spec.new, fspec.new

Column of wavelength and column of output power. Each column should be devided with space. Unit of wavelength should be [nm], and that of output power should be [dB]. *Don't insert comment line.* Second column is calculated spectrum from front facet, and third column is that of rear facet in `spec.new` and `fspec.new`.

Measured point in `spec.dat` should be less than 2000 points, and 200 points are calculated. Devide from starting wavelength to ending wavelength described in `spec.dat` into 200 equal intervals. So calculated output power in `spec.new` and `fspec.new` is 200 points.

When there are less than 200 points in `spec.dat`, spectrum are calculated at the written wavelength.

8.3 err.new

First line is the value of σ^2 and number of sampling points. On line 2 to line 6, first column is parameter, third column is fitted value, and second and fourth column is lower and higher error region.

8.4 peak.new

When the command `extract` or `initpar` is executed, this program recognize peaks and valleys of measured spectrum in `spec.dat`. These recognized peaks and valleys are written in `peak.new`.

9 Specified use

9.1 Example No.3

Known information • as cleaved GC-DFB. • first order grating and $\Lambda = 0.23693$[nm]. • $L = 550[\mu m]$

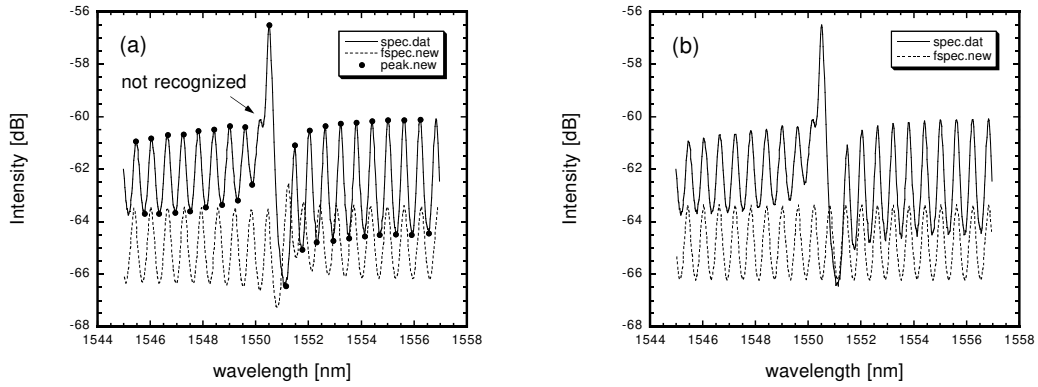

図 2: (a) Misread FP peak, (b) use `-f 1` flag

1. Copy `example3.dat` into `spec.dat`.
2. Execute

```
extract GCDFB 550 0.23693
```

3. Wait untill calculation is over. (in a few minutes)
4. Display `spec.dat` and `fspec.new` in the same graph to confirm the fitting was *not* succeeded.
   It is because initialized parameters were not appropriate.
5. Execute

```
initpar GCDFB 550 0.23693
```

6. Display `spec.dat` and `fspec.new` and `peak.new` in the same graph. And you can see that one small peaks are not recognized and calculated FP peaks are shifted from measured one (Fig.2(a)). It is because this program recognize that small peak as just a noise.
7. In this case, you input the command (`-f` means misread FP peaks)

```
initpar GCDFB 550 0.23693 -f 1
```

8. Display `spec.dat` and `fspec.new` in the same graph to confirm initialized parameters are appropriate (Fig.2(b)). (`peak.new` was removed.)
9. Execute

```
extract GCDFB 550 0.23693 -f 1
```

10. Wait untill calculation is over. (in a few minutes)
11. Display `spec.dat` and `fspec.new` in the same graph to confirm the fitting was succeeded.
12. Open the file `dfb.new` to see the value of extracted parameters. `example3.par` and `example3.spe` is the *correct* parameters and spectrum.
13. Copy `dfb.new` to `errparam.dat`.
14. Copy `example3.dat` (`spec.dat`) to `errspec.dat`.
15. Execute

```
anlyser.exe
```

16. — coffee break — (in a few *hour*)
17. Open the file `err.new` to see the value of extracted parameters. `example3.err` is the *correct* error region.

9.2 Example No.1

Known information • as cleaved GC-DFB. • first order grating and $\Lambda = 0.23693$[nm]. • $L = 550[\mu m]$

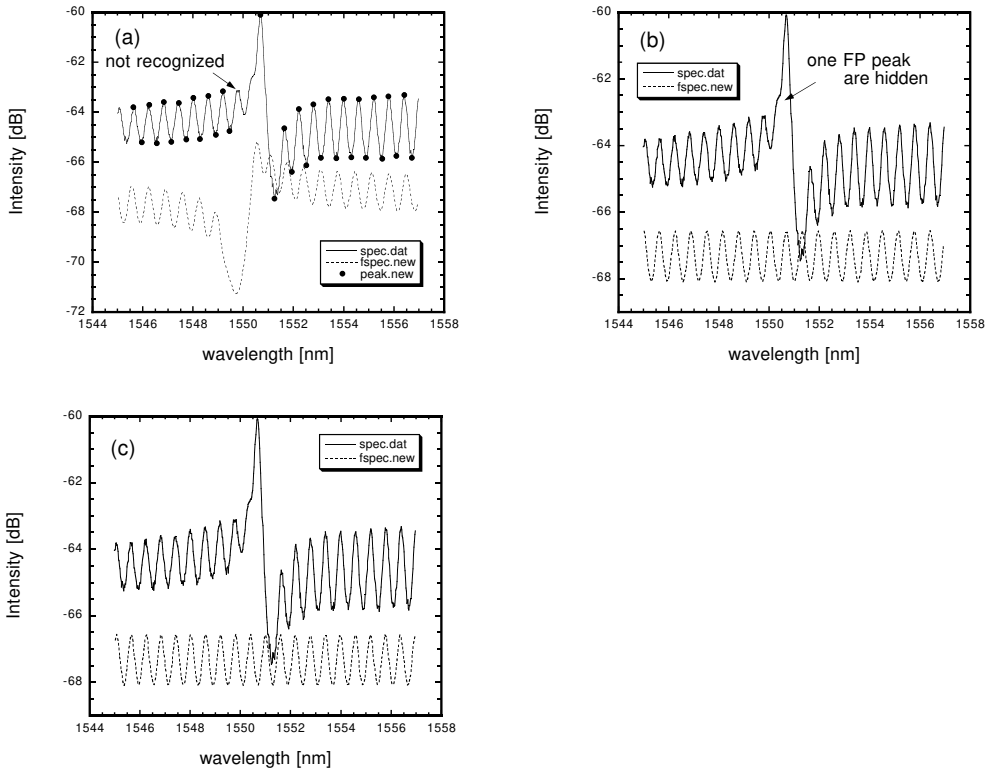

図 3: (a) Misread FP peak, (b) use `-f 1` flag, (c) use `-f 2` flag

1. Copy `example1.dat` into `spec.dat`.
2. Execute

```
extract GCDFB 550 0.23693
```

3. Wait untill calculation is over. (in a few minutes)
4. Display `spec.dat` and `fspec.new` in the same graph to confirm the fitting was *not* succeeded. It is because initialized parameters were not appropriate.
5. Execute

```
initpar GCDFB 550 0.23693
```

6. Display `spec.dat` and `fspec.new` and `peak.new` in the same graph. And you can see that one small peaks are not recognized and calculated FP peaks are shifted (Fig.3(a)).
7. You input the command

```
initpar GCDFB 550 0.23693 -f 1
```

8. Display `spec.dat` and `fspec.new` in the same graph to confirm initialized parameters are *not* appropriate (Fig.3(b)). It is because this program can't recognize the FP peak hidden in the main mode peak.
9. In this case, you input the command

```
initpar GCDFB 550 0.23693 -f 2
```

10. Display `spec.dat` and `fspec.new` in the same graph to confirm initialized parameters are appropriate (Fig.3(c)). (`peak.new` was removed.)
11. Execute

```
extract GCDFB 550 0.23693 -f 2
```

12. Wait untill calculation is over. (in a few minutes)
13. Display `spec.dat` and `fspec.new` in the same graph to confirm the fitting was succeeded.
14. Open the file `dfb.new` to see the value of extracted parameters. `example1.par` and `example1.spe` is the *correct* parameters and spectrum.
15. Copy `dfb.new` to `errparam.dat`.
16. Copy `example1.dat` (`spec.dat`) to `errspec.dat`.
17. Execute

```
anlyser.exe
```

18. — coffee break — (in a few *hour*)
19. Open the file `err.new` to see the value of extracted parameters. `example1.err` is the *correct* error region.

9.3 Example No.8

Known information • as cleaved GC-DFB. • first order grating and $\Lambda = 0.23693$[nm]. • $L = 550[\mu m]$

1. Copy `example8.dat` into `spec.dat`.
2. Execute

```
extract GCDFB 550 0.23693
```

3. Wait untill calculation is over. (in a few minutes)

4. Display `spec.dat` and `fspec.new` in the same graph to confirm the fitting *seems to be* succeeded.

5. Open the file `dfb.new` to see the value of extracted parameters. You find that net gain curvature is negative, and gain peak wavelength is too far from bragg wavelength. It is because that gain is expressed in three parameters, $g = \underline{g_1} + \underline{g_2}(E - \underline{E_p})^2$. When range of measured wavelength (12[nm] in example8) and net gain curvature is small, gain parameters cannot be extracted correctly. But the value of gain at measured wavelength are roughly correct (Fig.4).

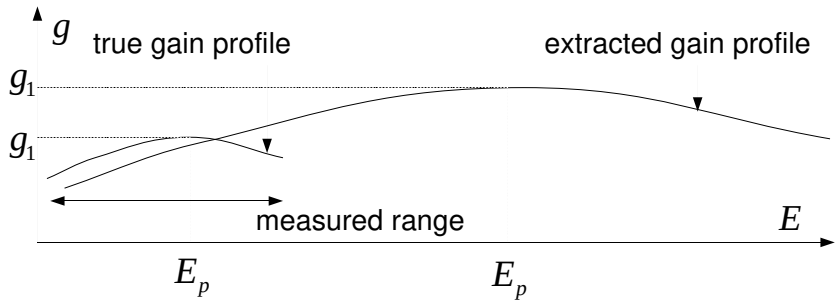

図 4: gain profile

6. If gain peak wavelength is fixed to appropriate value, net gain g_1 and net gain curvature g_2 is extracted correctly. As described in section 3, parameters of example8 is thought to be almost the same as those of example7, so you can use the *correct* parameters of example7 as initialized parameters for example8. And concerned about gain peak wavelength λ_p, you have decided λ_p of example7 as that of example8. Then copy to `example7.par` to `dfb.new` and edit this file. Change fitting flag of gain peak wavelength `1` to `0`.

7. Execute

```
fitting.exe
```

8. Wait untill calculation is over. (in a few minutes)

9. Parameters are extracted into the file `dfb.new`. So execute `fspec.exe` to calculate spectrum with using extracted parameters. Then fitted spectrum is written into the file `fspec.new`

10. Display `spec.dat` and `fspec.new` in the same graph to confirm the fitting was succeeded.

11. Open the file `dfb.new` to see the value of extracted parameters. `ex8.par` and `ex8.spe` is the *correct* parameters and spectrum.

12. Copy `dfb.new` to `errparam.dat`.

13. Copy `example8.dat` (`spec.dat`) to `errspec.dat`.

14. Execute

```
anlyser.exe
```

15. — coffee break — (in a few *hour*)

16. Open the file `err.new` to see the value of extracted parameters. `ex8.err` is the *correct* error region.

9.4 When some parameters are known

If you know the value of some parameters, such as front and rear facet phase for example, you can use such fixed parameters and apply fitting for other parameters. For example, you want to apply fitting to `example2` with using fitted parameters of `example1` as initialized parameters, and want not to change front and rear facet phase.

1. Copy `example2.dat` to `spec.dat`
2. Copy `example1.par` to `dfb.new`
3. Open the file `dfb.new` and change the fitting flag of front and rear facet phase `1` to `0`
4. Execute `fspec.exe` to calculate spectrum with using parameters in `dfb.new`.
5. Display `spec.dat` and `fspec.new` in the same graph to confirm that both of them resemble each other and `dfb.new` is valid as initialized parameters for fitting to `example2.dat`.
6. Execute

   `fitting.exe`
7. Wait untill calculation is over. (in a few minutes)
8. Parameters are extracted into the file `dfb.new`. So execute `fspec.exe` to calculate spectrum with using extracted parameters. Then fitted spectrum is written into the file `fspec.new`
9. Display `spec.dat` and `fspec.new` in the same graph to confirm the fitting was succeeded.
10. Open the file `dfb.new` to see the value of extracted parameters. Compared with `example2.par`, you find that extracted parameters are almost the same.

Program `extract` consists of three parts, calculate initialized parameters (`auto*.exe`), calculate spectrum with using given parameters (`fspec.exe`), and apply fitting (`fitting.exe`). The program `extract` only control these three function appropriately.

9.5 Example of batch file

When you measure many spectrum and want to apply fitting to all these spectrum, it is convinient to make batch file.

1. Copy one measured spectrum to `spec.dat`, and with using `initpar.exe`, you should know whether this spectrum need some flag like `-f 1` or not.
2. This work should be applied to all measured spectrum.
3. Edit batch file for fitting. In the example0 $\sim$ 8, batch file become `example.bat`
4. Execute

   `example.bat`
5. Wait until all calculations are over.
6. See fitting was succeeded or not for all cases. In this case, fitting for example8 is failed, so try again as described in subsection 9.3
7. Edit batch file for error estimation. In this case, batch file become `anlyser.bat`.
8. Execute

   `anlyser.bat`
9. Wait until all calculation are over.

10 Option

`-r` Specify the facet power reflectivity, like AR-HR coated lasers. Default : facet power reflectivity is calculated by $R = (\frac{n-1}{n+1})^2$.

`-i` Recognize bragg wavelength as intensity peak wavelength when calculate initialized parameters. Default : bragg wavelength is recognized as the center of stop-band.

`-f` Recognize hidden or small FP peak. With using this option, bragg wavelength is recognized as intensity peak wavelength when calculate initialized parameters.

`-fs` Recognize hidden or small FP peak. With using this option, bragg wavelength is recognized as the center of stop-band.

The option `-i`, `-f`, and `-fs` should not be used at the same time. But `-r` can be used with other option.

11 Etc.

- When you measure the sub-threshold spectrum for fitting, optical spectrum analyzer should be used in DOUBLE MONOCHROME MODE.
- When the span of measured spectrum is too large, this program can't extract correct value, especially coupling coefficient and facet phase. In this case, you had better cut the data of `spec.dat` before fitting. (empirically, spectrum with 15$\sim$20 FP peaks is valid)
- When valid initialized parameters aren't derived and fitting routine doesn't work well, you should change the parameter *yourself* to bring the calculated spectrum close to the measured one by editing `dfb.new` and calculate spectrum by `fspec.exe` before executing fitting routine.
- The most probable case of failure in fitting routine is concerned about gain. In some cases, net gain curvature g_2 is determined as negative number or gain peak wavelength λ_p is determined as far from bragg wavelength. In this case, you should edit the failed extracted parameter file `dfb.new` and change g_2 as `0`, λ_p as around bragg wavelength, and g_1 as appropriate value, and fitting flag of λ_p as `0`. After this changing, execute `fitting.exe` again. Which was described in subsec. 9.3.
- But even if gain is not extracted correctly, value of other parameters are correctly extracted (See `example8.par` and `ex8.par`). Don't so mind when these gain parameters are not appropriate.
- If measured laser has some unique points, like dark line in active layer, or nonuniformity along the cavity, or so, this fitting program can't give a good fit.
- About goodness-of-fit. "sigma2" is desired to be as small as possible. And "max round trip gain" should be smaller than 1 because this value is used as general proportion in sum of infinite geometric series.
- When you judge result of the fitting, you should always see measured spectrum and fitted one at the same time.
- Even if fitting seems to be succeeded, *person* should judge whether the result is correct or not finally.

12 Request

This fitting program and instruction manual was written by Tooru Nakura, Nakano Lab., Dept. of Elec. Eng., Univ. of Tokyo, Japan. Please send e-mail to my superviser if you get this program. Not me, because I graduate university and change my research subject.

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