Optical Limiting Characteristics of Fabry–Perot Microresonators at Third-order Nonlinear Absorption and Refraction of the Intracavity Medium

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Abstract: Calculating steady-state optical limiting characteristics of nonlinear Fabry–Perot resonators, we noticed that the input-output characteristic shape does not depend on any resonator parameter. The intracavity medium was assumed to have either third-order nonlinear refraction or absorption. In a double logarithmic diagram the input-output characteristic can be divided into two regions, linear and nonlinear, which are both almost straight lines with a relatively short curved section between them. The only dependent variable is the position of that curved section (limiting threshold). Simple relations between resonator parameters, nonlinear coefficients and the limiting threshold, enabling one to easily get nonlinear characteristics of such resonators whithout doing nonlinear calculations, are presented.

1 INTRODUCTION

In a nonlinear Fabry–Perot resonator (NFPR) indices of reflection and absorption of a medium contained between the mirrors depend on light intensity. Such resonators have been well studied since the second half of the 1970s. Theoretically predicted effects of optical bistability, differential gain and limiting have been experimentally observed for resonators containing Na vapors, nonlinear liquids (liquid crystals, nitrobenzene, CS_2), and solid plates of semiconductor. A detailed review of these works has been presented in (Abraham and Smith, 1982).

In general, application of NFPRs for creation of low-threshold nonlinear optical devices is promising because of two following reasons. Firstly, the resonator is a narrowband optical filter, for which spectral position of the line of transparency depends on the optical distance between the mirrors not on medium resonant properties. Along with it a small change in the refractive index of a medium contained between the mirrors results in a significant spectral shift of the line. Whereas a small increase in the absorption index drops considerably transmittance (T) at the peak of the line (however, in this case a decrease in T results mainly from an increase in reflectance (R) not from an increase in absorbance (A) of the whole structure). Secondly, light intensity at the resonant wavelength many-fold increases in the space between the mirrors by interference, which leads to a correspondent decrease in the nonlinear threshold.

An NFPR works as an optical power limiter if the incident radiation wavelength is a resonant wavelength. The potential of NFPR in the capacity of quick-response one-wavelength optical limiters is currently under investigation. Such limiters could be useful in a variety of laser systems, for example, in a laser rangefinder to protect the detector from intensive reflected (back-scattered) radiation. Currently there is a lack of experimental works realising that approach, whereas interest in optical power limiting is very active.

There are also some features restricting the range of possible application of NFPRs as optical limiters:

- an NFPR operates as an optical limiter only at a predetermined resonant wavelength while being simply a linear mirror in the neighborhood of this wavelength;
- an NFPR must be placed in a collimated beam propagating in a specified direction.

Recently we presented an experimental observation of optical limiting effect provided by a thin-film multilayer NFPR (Ryzhov et al., 2014). The experimental characteristics were in a good agreement with corresponding numerical simulation results. The

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same calculation program was used in the present work.

2 THE APPROACH

A monochromatic uniform plane wave, characterized by intensity $I_{\rm inp}$ and wavelength λ_0, enters into a symmetric NFPR, characterized by mirror reflectance $R_{\rm m}$, geometrical thickness L, intracavity medium linear refractive index n_0 and complex nonlinear coefficient n_2 (cm^2/W). There is no absorption in the mirrors and no linear absorption in the medium.

The intracavity medium is assumed to be a third-order nonlinear material with instant response so that at any location x

$$n(x) = n_0 + n_2 I(x), \tag{1}$$

where $I(x)$ is light intensity (W/cm^2) at location x.

The real part of n_2 defines nonlinear refraction and is commonly denoted as γ: $\gamma = \Re(n_2)$. Nonlinear absorption is usually characterized by coefficient β (cm/W), which is proportional to the imaginary part of n_2:

$$\beta = \frac{4\pi}{\lambda_0}\Im(n_2). \tag{2}$$

Optical limiting characteristic of an NFPR is either output intencity $I_{\rm out}$ or transmittance T dependence on input intencity $I_{\rm inp}$. In case of nonlinear absorption absorbance A versus $I_{\rm inp}$ can be considered as a separate characteristic.

Numerical simulation of optical limiting characteristics at different parameters of the NFPR shows that shapes of the characteristics are constant. More precisely, there is one shape when the medium has nonlinear absorption, and another (but quite similar) shape when the medium has nonlinear refraction.

When one or several parameters of the NFPR vary, its nonlinear characteristic only moves along the absciss. The characteristic position can be evaluated by just one value — the limiting threshold. We define the limiting threshold $I_{\rm th}$ as a value of $I_{\rm inp}$, at which T decreases to 0.8 of its initial value, which is a quite common definition:

$$T(I_{\rm th}) = 0.8T(0). \tag{3}$$

The task is to derive relations between $I_{\rm th}$, λ_0 and the NFPR parameters: $R_{\rm m}, L, n_0, n_2$.

3 NONLINEAR ABSORPTION

This section deals with the case when only nonlinear absorption exists and $\gamma = 0$. In Figure 1 limiting characteristics of such an NFPR in terms of $I_{\rm th}$ are presented.

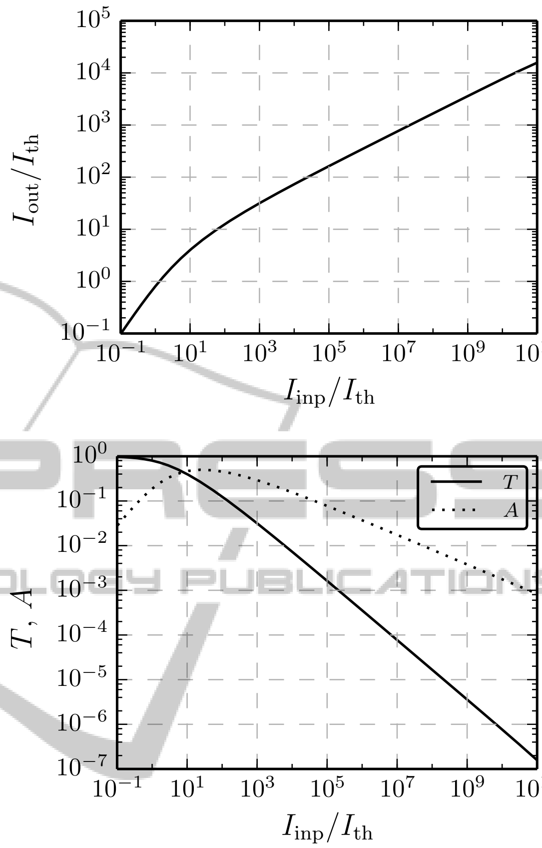

Figure 1: Limiting characteristics of an NFPR at nonlinear absorption.

A noticable feature of these characteristics is that absorbance A is at its maximum when $I_{\rm inp}$ is in the range $(10;100)\times I_{\rm th}$. Low A at high $I_{\rm inp}$ means that the absorptive medium is in some degree protected from optical breakdown or overheating by the mirror.

As it was mentioned above, light intensity at the resonant wavelength many-fold increases in the space between the mirrors. The field inside the resonator is a standing wave, and it is clear that in the absence of absorption intensity at the loops

$$\max\{I_{\rm inside}\} = \frac{4}{(1-R_{\rm m})} I_{\rm out} = \frac{4}{(1-R_{\rm m})} T I_{\rm inp}. \tag{4}$$

It is evident that $I_{\rm th}$ is inversely proportional to $I_{\rm inside}/I_{\rm inp}$ and β. It also must be proportional to the finesse of the resonator because the finesse, in some sense, determines the number of passes. So, for a high finesse NFPR ($1 - R_{\rm m} << 1$), the required equation can be written as

$$I_{\rm th} \simeq 0.07\frac{(1-R_{\rm m})^2}{L\beta}; \tag{5}$$

where the coefficient 0.07 was defined by the numerical calculations.

Recently a quite comprehensive theoretical analysis of the same case — plane microresonator at third-order nonlinear absorption of the intracavity medium — was published (Makri et al., 2014). One can find there a plot looking exactly like Figure 1, but there is no relation comparable to Equation 5.

4 NONLINEAR REFRACTION

Here it is assumed that only nonlinear refraction exists and $\beta = 0$. Limiting characteristic of such an NFPR in terms of I_{th} is shown in Figure 2.

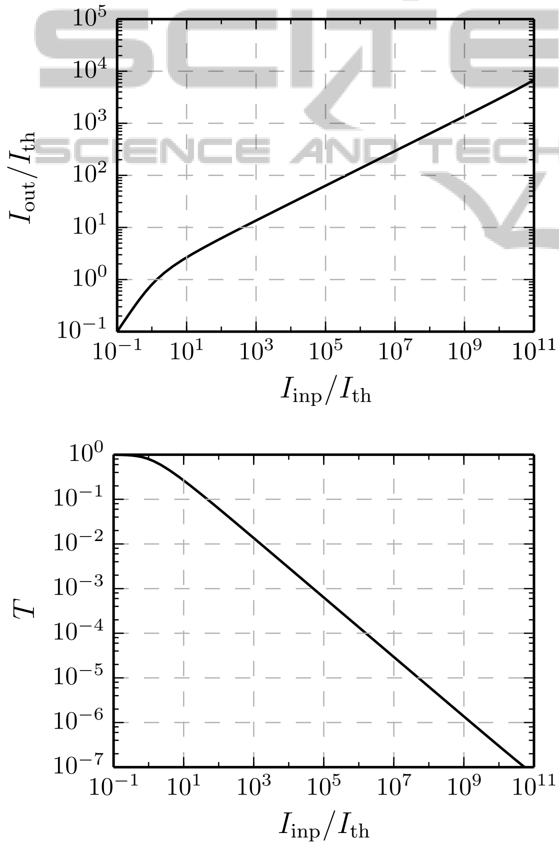

Figure 2: Limiting characteristics of an NFPR at nonlinear refraction.

As opposed to the case of nonlinear absorption, at nonlinear refraction T does not decrease with no limit. Considering that the decrease in T results from a spectral shift of the resonance line, one can easily realize that the minimal possible value of T is equal to the minimum of the initial (at very low I_{inp}) transmission spectrum. That value is well known from the theory of Fabry–Perot resonators:

$$T_{min} = \frac{(1-R_m)^2}{(1+R_m)^2}. \tag{6}$$

As far as T_{min} depends on R_m, it is different for NFPR with different R_m. So the presented limiting characteristic in terms of I_{th} is appropriate to an NFPR only for a range of I_{inp}, at which $T > T_{min}$ and the nonlinear characteristic is almost straight in a double logarithmic diagram. At higher I_{inp} T at first slightly increases, then jumps to higher branches — the input-output characteristic is multiple-valued. Of course, limiting characteristics of different NFPR are different in this area.

For example, the limiting characteristic of a specified NFPR, for which $I_{th} = 10$ (W/cm^2), is shown in Figure 3. Here $\lambda_0 = 1.5\ \mu\text{m}, R_m = 0.9988, L = 53.57\ \mu\text{m}, n_0 = 3.5, \gamma = 10^{-10}$ (cm^2/W).

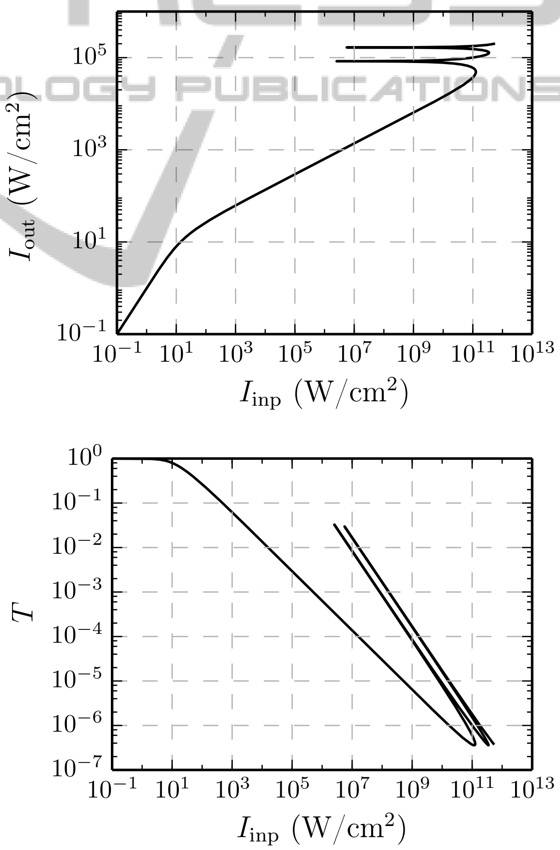

Figure 3: Multiple-valued limiting characteristics of an NFPR with specified parameters.

In fact upper branches of T reach unity. It is not shown in the given plot due to a lack of calculation points, although their number is very high — 951 points in the range of I_{out} from $1.5 \cdot 10^4$ to $2 \cdot 10^4$ W/cm^2.

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Unlike the case of nonlinear absorption, at nonlinear refraction $I_{\rm th}$ is inversely proportional to $\delta\lambda$ — the full-width half-maximum of the resonant line. $I_{\rm th}$ also must be inversely proportional to $I_{\rm inside}/I_{\rm inp}$ and γ. Finally, for a high finesse NFPR the following equation was derived:

$$I_{\rm th} \simeq 0.16(1-R_{\rm m})\frac{n}{\gamma}\frac{\delta\lambda}{\lambda_0}. \qquad (7)$$

By means of the linear Fabry–Perot resonators theory $\delta\lambda$ can be expressed through other variables:

$$\delta\lambda = \frac{1-R_{\rm m}}{\pi\sqrt{R_{\rm m}}}\frac{\lambda_0^2}{2n_0L}; \qquad (8)$$

so that

$$I_{\rm th} \simeq 0.025\frac{(1-R_{\rm m})^2}{\gamma\sqrt{R_{\rm m}}}\frac{\lambda_0}{L}; \qquad (9)$$

or, if $(1-R_{\rm m}) << 1$,

$$I_{\rm th} \simeq 0.025\frac{(1-R_{\rm m})^2\lambda_0}{\gamma L}. \qquad (10)$$

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5 CONCLUSION

The derived simple equations (5) and (10) enable one to estimate the limiting threshold of an NFPR in cases of third-order nonlinear absorption or third-order nonlinear refraction of its intracavity medium. Together with the limiting characteristics in relative units (Figures 1 and 2) these relations easily give corresponding absolute limiting characteristics, so that there is no need to calculate them for each new set of NFPR parameters.

The following additional consequences can be formulated:

1. At given parameters of the intracavity medium (L, n_0, n_2) an increase in mirror reflectance $R_{\rm m}$ leads to an increase in the field intensity multiplication (inside relative to outside) and a decrease in resonance line width $\delta\lambda$. All that results in quadratic reduction of the limiting threshold $I_{\rm th}$ which is proportional to $(1-R_{\rm m})^2$ at both nonlinear absorption and refraction.
2. With the other things being equal an increase in the resonator length L leads to proportional decreases in $\delta\lambda$ and in $I_{\rm th}$ also at both nonlinear absorption and refraction. In this case the rate of $I_{\rm th}$ reduction with $\delta\lambda$ narrowing is lower. To realize that one should take into account that the field intensity multiplication depends only on $R_{\rm m}$. So if a decrease in $I_{\rm th}$ is needed but a narrower resonant line is undesirable, it is more advantageous to enhance $R_{\rm m}$ not L.

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