Observation of parity-time symmetry in electrically pumped FP laser

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Abstract

Parity-time (PT) symmetry is a new method to get single mode operation in lasers, mostly, micro-ring lasers. In this study, we propose and experimentally demonstrate an electrically pumped PT symmetric Fabry–Perot (FP) laser which can work with a mode selection. The proposed laser could achieve the PT symmetric condition by an electrical manipulation of the interplay between gain and loss in two FP resonators. The single mode lasing is demonstrated at 1574.6nm with a 20.81dB sidemode suppression ratio.

Introduction

Since the early days of lasers, the goal of getting single-mode operation has driven development of cavity design \cite{1}. At very first, Fabry–Perot (FP) optical resonator is widely used in lasers’ cavities design. However, although FP lasers have advantages like simple structure and low processing difficulty, this kind of resonator can’t achieve a single-mode lasing very well which leads to fewer and fewer FP LDs. Consequently, some additional steps in cavity design have been done to achieve a single-mode operation. There are several ways to achieve that, such as, addition of intracavity dispersive elements like distributed feedback gratings or distributed Bragg mirrors \cite{2}-\cite{4}, coupling to external cavities \cite{5}, and shaping the spatial profile of a pump light to a laser cavity \cite{6}. And electrical injected semiconductor lasers contain above-mentioned structure like distributed feedback (DFB) lasers, distributed Bragg reflector (DBR) lasers and vertical-cavity surface-emitting lasers (VCSELs) are widely used now for their large sidemode suppression ratio, low threshold, high efficiency and small footprint \cite{7}. However, these schemes have increasing the complexity of design and difficulty of fabrication, like the fabrication of DFB lasers usually involves one or more regrowth steps. In contrast, resonator like micro-ring and FP obviously have a huge superiority in implement single-mode selection in multi-mode laser cavity and been heavily researched \cite{14}-\cite{20}.

Mode selection based on PT symmetry of lasers is achieved by control the interaction between gain and loss in two resonators. When the balance between gain and loss is reached, a PT-symmetry is formed and a mode selection occur. The cavities of PT symmetric lasers mostly uses two micro-ring resonators, who have high Q factor and easy to control the coupling efficiency. To achieve single mode selection, PT symmetric micro-ring lasers can work in single-mode emission by light or electric injection \cite{14}-\cite{20}. But FP resonators didn’t draw people’s attention in PT symmetry research for its low Q factor and complexity in resonation and coupling.

In this study, we propose and experimentally demonstrate an electrically pumped FP laser which achieves a mode selection based on PT symmetry. Two FP resonators, which are controlled by two independent electrodes, take over the mostly used micro-ring resonators. The gain and loss of two FP resonators change with the current injection on each electrode. And the coupling constant is controlled by distance between the two FP resonators. An electrical pumped FP laser who have advantages like small size, simple structure and low fabrication difficulty can achieve a 20.81dB sidemode suppression ratio at 1574.6nm.

Basic principle.

The concept of PT symmetry was proposed in quantum physics theory first \cite{8}. After that, it was found that the form of PT symmetry had good compatibility with the result of optical experiment \cite{12}. In PT symmetry theory, an optical system is a PT symmetric system if the complex refractive index distribution follows the
relationship of $n^*(-r) = n(r)$, which means the system has equal gain and loss. This leads to a lot of researches in active optical devices based on PT symmetry pumped by optic or electric, which are micro-ring structure mostly. And in theory, the PT symmetry can also occur in FP optical resonators.

The schematic of proposed electrically pumped PT symmetric FP laser is shown in figure.1. This kind of laser consists of two FP resonators and two independent electrodes. When the current on electrodes exceeds threshold current of single FP laser, a gain occurs in that FP laser. On the other hand, when the injection current is fewer than threshold current, a loss occurs in the single FP laser and it couldn’t lase. According to this method, the gain and loss of two FP resonators are controlled independently. Though controlling the distance between two FP resonators during fabrication, the coupling coefficient is manageable to achieve a PT symmetry.

In the time domain, a resonator could lase several longitudinal modes, the n-th longitudinal mode in each FP resonators obey two coupled differential equations given by

$$\frac{da_n}{dr} = -j\omega_n a_n + \gamma_{a_n} a_n$$  \hspace{1cm} (1)
$$\frac{db_n}{dr} = -j\omega_n b_n + \gamma_{b_n} b_n$$  \hspace{1cm} (2)

where $a_n$ and $b_n$ are respective mode amplitudes, $\gamma_{a_n}$ and $\gamma_{b_n}$ represent gain or loss in each FP resonator, $\kappa$ is the coupling coefficient between two FP resonators and $\omega_n$ is the angular frequency of the n-th longitudinal mode. According to equation (1) and (2), the eigen frequencies $\omega_n^{(1,2)}$ of the system of the two supermodes are given by

$$\omega_n^{(1,2)} = \omega_n + j \frac{\gamma_{a_n} + \gamma_{b_n}}{2} \pm \sqrt{\kappa_n^2 - \left(\frac{\gamma_{a_n} - \gamma_{b_n}}{2}\right)^2}$$  \hspace{1cm} (3)

To achieve PT symmetry, $\gamma_{a_n} = -\gamma_{b_n}$ is necessary and equation (3) can be simplified to

$$\omega_n^{(1,2)} = \omega_n \pm \sqrt{\kappa_n^2 - \gamma_{a_n}^2}$$  \hspace{1cm} (4)

Obviously, if the gain and loss (which are equal as $\gamma_{a_n}$ now) of a pair of modes less than the coupling coefficient, as $\gamma_{a_n}(\omega) < \kappa_n(\omega)$, the eigen frequencies $\omega_n^{(1,2)}$ will remain neutral. However, if the gain and loss exceed the coupling coefficient, as $\gamma_{a_n}(\omega) > \kappa_n(\omega)$, the PT symmetry will be broken and a supermode will get more energy from another disappeared supermode which shows a single mode selection.
Device design and fabrication.

To meet the needs of proposed laser's fabrication, an InAlGaAs/InP structure is grown on an undoped InP substrate by MOCVD which is shown in figure.2. Because both dry-etching and wet-etching are used to fabricate ridge waveguides, a thin etch stop layer is deposited to ensure the depth of etching equaling designed depth. And on the top of wafer, a contact layer is deposited to achieve the Ohmic contact between p-cladding and p-electrode.

Figure 2: The epitaxial structure of component in the proposed FP laser.

Figure 3: The fabrication of electrically injected PT symmetric FP laser. (a) The schematic of wafer is shown. (b) Negative tone resists is spun onto the wafer. And the pattern is defined by mask. (c) Cavities of FP resonator are etched. Both dry-etching and wet-etching are used to fabricate two ridge waveguides. (d) SiO$_2$ layer is deposited by PECVD. (e) BOE is used to open the window for electrodes on twin cavities. (f) P-contact electrodes containing Au/Ge/Ni are deposited. After the thinning of substrate, n-contact electrode consist of Ti/Pt/Au is deposited.
The standard nanofabrication is used as shown in figure.3. In PT symmetry theory, two same resonators which have same longitudinal multi-modes are needed. So, the width and depth of two ridge waveguides are identical to get two same FP resonators. In ridge waveguides designing, the widths of two ridge waveguides are both 2um, which can ensure single transverse mode in each resonator. And the depth is about 1.8um including contact layer and p-cladding layer. Distance between two resonators is 1.5um to get a proper coupling efficiency. In fabrication of ridge waveguides, both dry-etching and wet-etching are used to get a good appearance of ridge waveguides which have good optical restriction. The scanning electron microscope image of ridge waveguides are shown in figure.4. After that, the SiO₂ and two p-contact electrodes are deposited. Then, the substrate thinning and n-contact electrode deposition are finished. At last, the wafer is cleaved into chips and optical films are coated on emission surface and back surface to enhance the output power.

![Figure 4: Scanning electron microscope image of two coupled ridge waveguides.](image)

**Experiment and results**

![Figure 5: The light-current characteristics.](image)
The cleaved chips have a 300um width and 600um cavity length. First of all, the light-current characteristics of single FP laser and proposed PT symmetric FP laser are tested. As shown in figure 5, the threshold current of both single FP laser and twin laser cavities of PT symmetric FP laser is about 17 mA. When the injected current exceeds threshold current, the optical field in FP resonator gets a power gain and start lasing. On the other hand, if the injected current is less than threshold, there is no emission, and the same time, power in resonator endure power loss. Different P-I curves show that each single laser in PT symmetric FP laser works on its own and have similar P-I characteristic of tradition single FP laser.

To meet the need of twin current injection at the same time, the chips are packaged by TO shelled headers. The proposed chip and packaged laser are shown in figure 6. For PT symmetry testing, an electrically driven laser test platform is built as shown in figure 7. And a bare fiber is adjusted location by six axes stage to receive LD's optical power, which is guide by optical power meter and optical spectrum analyzer to get the power and spectrum of LD. And the packaged LD is driven by two laser diode controllers, which can manipulate the gain and loss of each single FP resonator. The proposed PT symmetric FP laser is tested under two different working situations. In contrast, single FP laser is also test to show differences between twin PT symmetric FP laser and traditional single FP laser in optical spectrum.

In this experiment, the gain and loss are controlled by laser diodes controllers which can provide continuing current injection. And the spectrums of single FP lasers and PT symmetric FP lasers tested by optical spectrum analyzer (OSA) are shown in figure 8. In figure 8(a), a traditional single FP laser emits standard multi-mode spectrum. This FP laser is driven by a continuing current beyond threshold current. And as shown in figure 8(b), the PT symmetric FP laser driven by two continuing current emits a spectrum who has a 20.81 dB sidemode suppression ratio (SMSR) at 1574.6nm. In this FP laser, one FP laser is pumped by a current over threshold current.
which means this resonator gets a power gain and another FP laser is pumped by a current below threshold current which means this resonator endures a power loss. The gain and loss reach a balance by controlling two current. And after the modes exchange power by the coupling between two FP resonators, a single mode selection occurs. In contrast, if two FP lasers get current whose value exceeds threshold current respectively and simultaneously, the OSA shows a multi-modes spectrum again. And each single mode in multi-modes is split in two as shown in figure.8(c). These results show that two FP resonators can get a PT symmetric working situation and electrical injected twin FP lasers can achieve a single mode selection based on PT symmetry.

![Figure 8](image.png)

**Figure 8 Experiment results to show mode suppression and split in different situation of PT symmetry.** (a) Multi-modes spectrum of traditional single FP laser is observed. (b) Single mode lasing at 1574.6nm with a 20.81dB SMSR is achieved by the broken of PT symmetry. (c) The splitting in resonance frequency is observed when both FP resonators are working in gain situation.
Conclusion

In conclusion, we have proposed and experimentally demonstrated an electrically pumped FP laser which can work in PT symmetric situation. The power in PT symmetric FP laser shows gain or loss by tuning the current beyond or below threshold current. And a 20.81dB sidemode suppression ratio is achieved by breaking the PT symmetric. Thanks to the simple structure of FP resonator, the difficulty in design and fabrication of twin FP resonators is low. It is a new design of electrically pumped PT symmetric laser which can work in single mode and may have a variety of applications.

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