CHAPTER 3

TUNABLE LIQUID CRYSTAL FILTERS

Several types of liquid crystal elements have been successfully developed as intracavity wavelength tuning elements. These elements can be categorized as birefringent filters [47-54], Fabry-Perot étalons or interferometers [55-58], or spatial light modulators (SLM) [59-65].

3.1 Birefringent filters

Electronically tuned birefringent filters can be realized using the electro-optic properties of liquid crystals (LC). A LC based electro-optic filter exhibited many attractive features: (1) High transparency over a large spectral range and large birefringence which potentially lead to broadband devices with very large tuning ranges. (2) A large birefringence change usually can be achieved by a relatively small voltage as low as several volts. This is typically much lower than the voltages required for other bulk electro-optic crystals. (3) No deviation in the outgoing beam takes place. (4) The device fabrication is simple and the cost is low.

The principle of the birefringent filter was first suggested by the French astronomer Benard Lyot in 1933. According to Lyot [47], a filter is constructed by using a plurality of birefringent elements, the thicknesses of which vary in geometrical progression d, 2d, 4d,…, 2^{N-1}d. The filter elements were made of quartz and had their faces parallel to each other and normal to the light rays. Their optical axes are parallel to one another and forming 45° angles with the planes of polarization of polarizers sandwiched between each cell. Transmission through each segment (plate plus polarizer) will vary sinusoidally, with maxima at wavelengths for which the retardation of the plate is a multiple of 2π. For each segment, the separation between transmission maxima and the FWHM of one of the maxima is inversely proportional to the plate thickness. Thus, the transmission spectrum for the entire stack will consist of narrow bands having the FWHM of the thickest plate and separated by the free spectral range of the thinnest plate. The disadvantage of the filter described by Lyot is that it is very expensive and was designed for use at a single frequency, having very limited tunability. Lyot-type filters employing zero-twist, nematic-phase, liquid crystal cells as variable retarders have been realized [48, 49]. The structure is a parallel-aligned LC cell under crossed polarizers. The director's axis of the LC is at 45° to the axis of the polarizer. The operation principle is based on the phase retardation experienced by each linearly polarized light while traversing through a birefringent plate. These phase retardations are then analyzed by an analyzer resulting in amplitude modulation of each beam. A voltage is applied to the LC cell to control the phase retardation of each beam so that the filter transmits only one beam with high efficiency and, in the mean time, reflects completely the others. The tuning performance of a six-stage, liquid-crystal tunable, Lyot filter has been investigated by Staromlynska *et al.* [50]. The schematic of the Lyot filter is shown as in Fig. 3.1. In the designed filter, passive birefringent elements (lithium niobate crystals), and liquid-crystal wave plates were used to determine the spectral characteristics (free spectral range and linewidth) and to achieve accurate peak placement and wavelength tuning. The filter was designed to have a narrow bandwidth of 0.1 nm and can be electro-optically tuned to give a transmission maximum at any wavelength within the visible range.

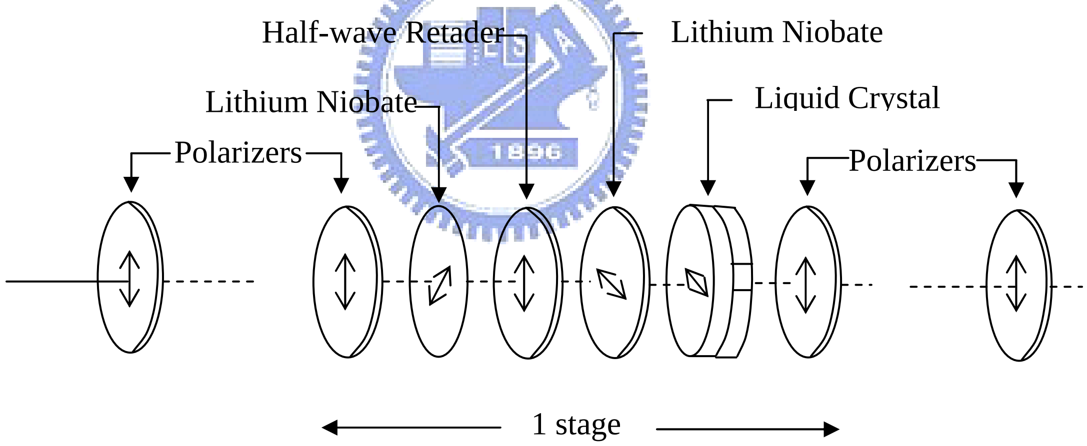

Fig. 3.1 Lyot filter [50]

Incorporating birefringent filter in the external cavity of an ECDL has been constructed [51-53]. John R. Andrew demonstrated to scan the laser electronically over 10.3 nm, hopping single modes of the external cavity, by using a six-stage birefringent filter [52]. Each stage of the filter contains a passive birefringent crystal and a nematic liquid crystal (NLC, E7) cell. Tuning of the laser wavelength is accomplished with an electrically controlled birefringence NLC cell in each stage of the filter. By changing the voltage to the two smallest FSR stages of the birefringent filter, continuous tuning of 182 MHz was achieved. The tuning mechanisms were operated at <2 V. B. Wacogne *et al.* proposed a simpler configuration involving two LC cells and a single birefringent plate [53]. The two LC cells work as a one stage Lyot filter for the 45° polarized light emitted by the laser chip. Single mode tuning over a 6 nm range by hopping modes and continuous tuning inside one free spectral range of the external cavity were demonstrated. The driving voltages are smaller than 10 V, which are 10^3 times lower than those using $LiNbO_3$ crystals as wavelength selective elements. A tunable fiber laser was constructed with an intracavity birefringent tuner [54]. The tuner consisted of a birefringent quartz plate and an E-O LC cell, and was set between crossed polarizers. The tuning range of 17 nm and the tuning rate of 8 nm/V were reported.

3.2 Fabry-Perot étalon filters

The basic structure of the liquid-crystal Fabry-Perot (F-P) étalon filter is shown as in Fig. 3.2 [55]. It is an F-P interferometer containing a homogeneously aligned NLC in the cavity. The NLC layer lies between two dielectric coated glass plates. The reflectivity determines the reflection finesse. An electric field is applied to the LC via transparent indium tin oxide (ITO) electrode layers that are deposited on the inner surfaces of the glass. The outer glass surfaces are AR coated to prevent the formation of additional cavities. Without any application of external field, the molecules of the LC are aligned along the plane of the F-P surface, in a direction determined by the rubbing direction of the glass plates. When an external field is applied, the molecules rotate toward the propagation direction so that the refractive index is changed for the light linearly polarized along the rubbing direction. In the F-P resonator, the change in the refractive index causes a change in the optical path length and the passband of the LC filter is electrically tuned. The advantage of using a Fabry-Perot structure rather than a birefringent filter is the enhanced tuning range and frequency selectivity.

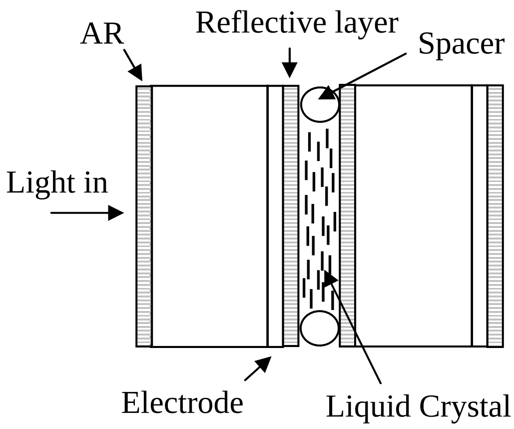

Fig. 3.2 Liquid-crystal Fabry-Perot étalon filter [55]. AR: anti-reflection coating

M. W Meada *et al.* applied the LC F-P étalon filter in a tunable fiber laser [56]. A 10-μm-thick NLC layer lies between two reflectively coated glass plates. The reflectivity is 98.5 % and the filter bandwidth is 0.4 nm with a FSR of over 60 nm. With a voltage of only 2.1~3.3 V applied to the filter, the wavelength is tunable over 45 nm (1523~1568 nm), limited primarily by the gain bandwidth of the erbium-doped fiber amplifier. H. Tsuda *et al.* constructed an ECDL with a LC F-P interferometer (LC-FPI) wavelength-selective filter [57].

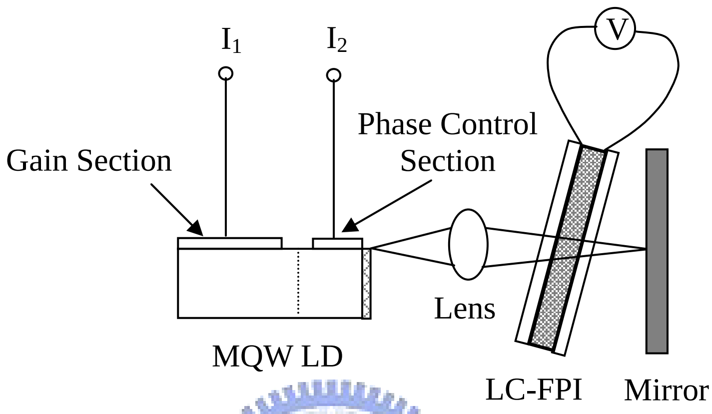

Fig. 3.3 ECDL uses a LC-FPI and a MQW laser diode [57]. MQW: multi-quantum-well; LD: laser diode

Single-mode lasing occurs only when one of the external modes, one of the internal modes, and the LC-FPI transmission peak are brought into convergence by controlling the applied voltage to the LC-FPI and the injection current to the phase control section of the multi-quantum-well (MQW) LD. They demonstrated a tuning range of 41 nm. The slope of the lasing wavelength versus applied voltage was ~5 nm/V. The tunable LC-FPI filters can also be applied in wavelength-division multiplexing communication systems [58].

3.3 Spatial light modulators

A LC spatial light modulator (SLM) consists of an array of electrically addressable elements (pixels) with a LC modulating layer. Each pixel acts independently as an optical valve to adjust or modulate light intensity from the light source. Parker and Mears have demonstrated an architecture combining a SLM written dynamic hologram and a fixed diffractive grating to produce a tunable wavelength filter with a tuning resolution of 2.5 nm over a 160 nm range [59]. The pixilated ferroelectric LC-SLM was used as a digitally programmable diffractive grating in a system to perform optically transparent wavelength filtering (Fig. 3.4).

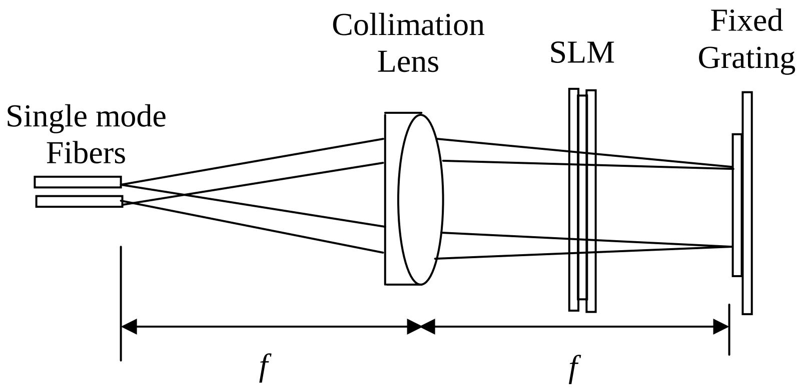

Fig. 3.4 The tunable wavelength filter by combining a SLM and a fixed grating [59]. SLM: spatial light modular; *f*: focal length

The SLM is a transmissive multiplexed glass cell with 128×128 μm pixels on a 165-μm pitch that has been thickness optimized for operation around the λ=1.5 μm and can be reconfigured in under 5 ms.

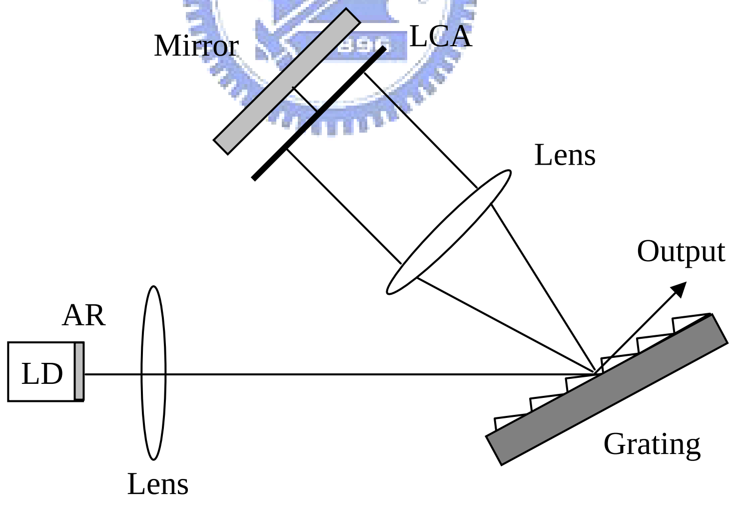

Fig. 3.5 An ECDL tuned with an intracavity liquid crystal array [65]. AR: anti-reflected coating; LCA: liquid crystal array

Parker and Mears also incorporated the ferroelectric LC-SLM in a fiber ring laser to tune discrete wavelengths spaced by 1.3 μm over a range of 38.5 nm [60]. Pan *et al.* have reported LC-SLM based tunable optical filtering devices for dense WDM communication [61, 62]. A tunable semiconductor laser with liquid crystal pixel mirror (LCPM) based on the LC-SLM technology in grating-loaded external cavity were developed. The LCPM was based on the design of a normally off-state twisted NLC cell. The cell was constructed with a NLC layer sandwiched between ITO glass plates. One of the ITO-electrodes was patterned with fifty 100×2 cm stripes with 5 μm spacing. An Au-coated substrate was attached behind as a back mirror. Digitally tuning of an ECDL at wavelength of 650 nm, 830 nm and 1.5 μm were demonstrated [63, 64]. J. Struckmeier *et al.* presented an electronically tunable diode laser by insertion of a liquid crystal array (Fig. 3.5). Wavelength tenability over a range of 10 nm with a 670 nm LD was demonstrated [65].