Photon Band Structure in a Sagnac Fiber-Optic Ring Resonator

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(Received 11 May 1988)

We show experimentally that propagation of light waves in an effectively rotating fiber-optic ring resonator leads to a photon band structure due to interference of elastically scattered waves. The rotation is simulated by means of a Faraday-active element in the ring.

PACS numbers: 42.50.−p, 42.81.Pa, 71.55.Jv

Recently, much study has been devoted to the analogy between quantum waves and classical waves, based on the equivalence of the corresponding wave equations.[1-6] Usually the quantum waves involved are electronic and the classical ones electromagnetic, i.e., light waves. Interest has centered on classical analogies of quantum concepts associated with interference of elastically scattered waves with primary waves. Examples are weak and strong localization,[1-4] due to scattering from a random medium, and the occurrence of band structures, due to scattering from a periodic medium.[7,8] Such studies have a cross-fertilizing effect on solid-state physics and optics. In this Letter we report on the experimental realization of a novel type of photon band structure, recently predicted by Lenstra, Kamp, and van Haeringen,[5] due to interference of elastically scattered waves in a rotating ring resonator (Sagnac interferometer). The rotation-induced phenomena in the Sagnac ring can be seen as the optical analog of the Aharonov-Bohm flux-periodic phenomena in a small normal-metal ring, where the magnetic flux encompassed by the ring introduces a round-trip phase difference between counterpropagating electronic waves.[9] In the optical case the role of the magnetic flux is played by twice the product of the rotation rate and the ring area, i.e., the rotation, flux; the latter introduces a round-trip phase difference via the Sagnac effect. Whereas the flux period equals h/e in the electronic case, it can be written as h/m_{ph} in the optical case, with m_{ph} the photon mass $h\nu/c^2$.

We briefly sketch the essence of the theory.[5] Consider light waves propagating clockwise (cw) and counterclockwise (ccw) in a closed circular loop of single-mode fiber[10] of length L, where the whole structure rotates uniformly at angular frequency Ω [Fig. 1(a)]. As a result of the Sagnac effect the eigenfrequencies for cw and ccw light waves are different; a frequency spectrum $\omega(\Omega)$ of straight lines results which cross at $\Omega = M\pi nc/mL$, where M and m are integers ($M \ll m$), m being the longitudinal mode index of the ring and n the refractive index [Fig. 1(b)]. In the crossing points the cw and ccw waves will be coupled by inevitable backscattering due to static inhomogeneities in the ring. This coupling will lift the degeneracy, transforming crossings into anticrossings and thus leading to forbidden frequency gaps.[11] Adopting a scalar-wave description (i.e., neglecting fiber birefringence), the band structure $\omega(\Omega)$ near a specific crossing point (ω_i, Ω_j) is given by [5]

$$\omega_{\pm} = \omega_i \pm \tfrac{1}{2}\omega_i \left[\frac{L^2}{n^2\pi^2c^2}(\Omega - \Omega_j)^2 + \left(\frac{\Delta\omega_g}{\omega_i}\right)^2 \right]^{1/2}, \tag{1}$$

where $\Delta\omega_g$ is the width of the forbidden gap, $\Delta\omega_g = (\sqrt{\gamma}/\pi)\Delta\omega_{\mathrm{FSR}}$ with $\Delta\omega_{\mathrm{FSR}}$ the free spectral range of the ring resonator and γ the elastic intensity backscattering coefficient per round trip.

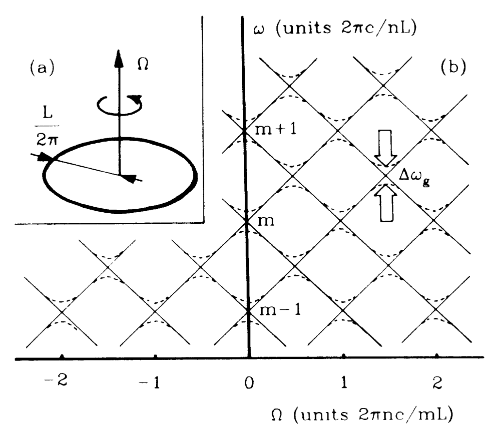

FIG. 1. (a) Essence of the Sagnac photon band structure in a ring resonator consisting of a closed circular loop of single-mode fiber. (b) In the absence of backscattering the eigenfrequency spectrum consists of two sets of parallel lines, corresponding to cw and ccw waves (solid lines). Elastic backscattering lifts the degeneracies, transforming crossings into anticrossings (dashed curves).

The experimental setup is shown in Fig. 2. The ring has planar geometry and is made of single-mode fiber (Lightwave Technologies, F1506C)[12]; $L=3.26$ m, corresponding to $\Delta\omega_{FSR}=2\pi\times 63$ MHz. Linearly polarized light from a single-frequency 632.8-nm HeNe laser (NRC, type NL-1) with 100-kHz linewidth, is coupled clockwise into the ring through a low-loss (1.0%) fused directional coupler DC1 (Aster, SM633 99/1/A) with an intensity cross-coupling coefficient of 0.01. Backscattering is supplied by Fresnel reflection from the air-glass interfaces of two aligned fiber ends, separated by a variable gap R. The width d of the air gap (typically a few micrometers) may be tuned to provide control of γ. In order to avoid problems with mechanical stability we have opted to simulate the rotation of the ring by means of a Faraday-active element, i.e., part of the fiber ring passes through a solenoid F. This variant clearly requires a vector wave description of the band structure, including effects of fiber birefringence.[13] We have used a configuration where it is easy to predict the polarization eigenmodes: both sections of the ring between air gap and solenoid (i.e., sections R-QW1-F and R-QW2-F) behave effectively like quarterwave linear retarders, represented by QW1 and QW2. The relative orientation of QW1 and QW2 is such that they compensate each other, resulting in vanishing round-trip birefringence of the ring. If there were no backscattering, the eigenmodes in this configuration would be circularly polarized (σ^+ or σ^-) inside F. Each of these (σ^+ and σ^-) would have twofold degeneracy (cw and ccw). Backscattering at the air gap causes a coupling between counterpropagating waves with opposite circular polarization inside F, since at the air gap these waves have the same linear polarization due to the presence of QW1 and QW2. As a consequence of the Faraday effect, these waves with opposite circular polarization inside F experience different optical path lengths, which establishes the analogy with mechanical rotation. It can be shown that this configuration is formally equivalent to the rotating Sagnac interferometer with backscattering.[13] One can define an effective rotation rate $\Omega_{eff}=VNInc/mL$, where N is the number of solenoid turns, I the solenoid current, and V the Verdet constant of the fused-silica fiber, defined such that the angle of rotation θ of linearly polarized light propagating through an axial magnetic field H along a distance l is given by $\theta=VHl$. Experimentally, element QW1 is realized by a small inplane subloop of fiber, the radius of which is adjusted to introduce the proper amount of bending-induced linear birefringence.[14] Element QW2, which produces the opposite quarterwave retardation, represents the net effect of two birefringent elements not shown in Fig. 2. The first of these is a subloop of fiber wound around a piezocylinder and the second a standard three-element polarization controller.[14,15] The piezocylinder is used to scan the length L of the ring, which is equivalent to scanning ω. Transmission spectra $I_T(kL)$ and reflection spectra $I_R(kL)$ can thus be measured; a directional coupler DC2 (50%/50%) outside the ring is used to measure the latter

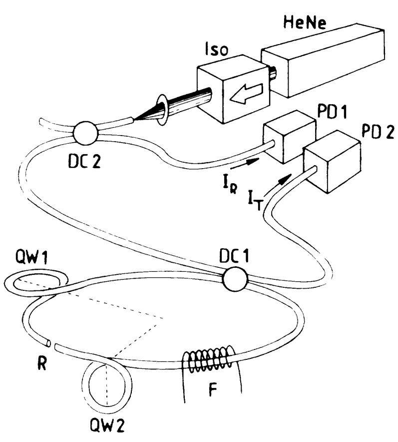

FIG. 2. Experimental setup. Iso is an optical isolator, DC1 and DC2 are directional couplers with coupling ratios of 0.01 and 0.50, respectively, so that only a small fraction of incoming light is coupled into the ring. F is a solenoid to simulate mechanical rotation, QW1 and QW2 are orthogonal quarterwave retarders and R is an air gap supplying Fresnel reflection. Photodiodes PD1 and PD2 measure the reflection and transmission signals, I_R and I_T, respectively.

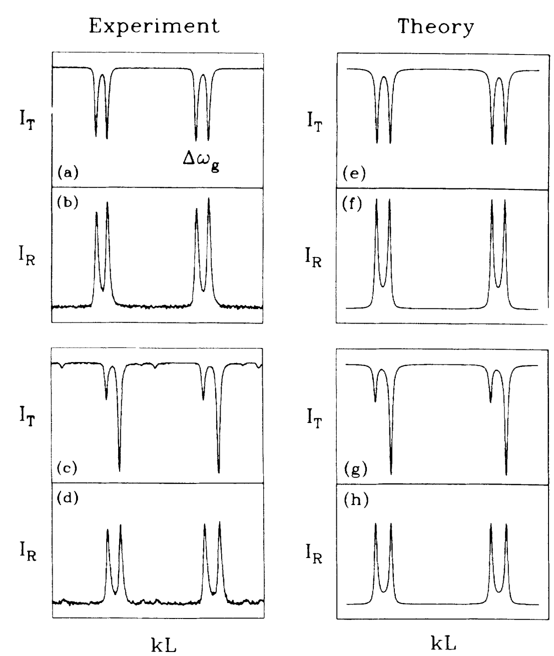

FIG. 3. Measured and calculated transmission and reflection spectra, $I_T(kl)$ and $I_R(kL)$. The upper four spectra are for zero effective rotation rate ($\Omega_{eff}=0$). The lower four are for $\Omega_{eff}=4.4$ rad/s. Spectra have been obtained by piezoscanning the ring's circumference L; the free spectral range is $\Delta\omega_{FSR}=2\pi\times 63$ MHz.

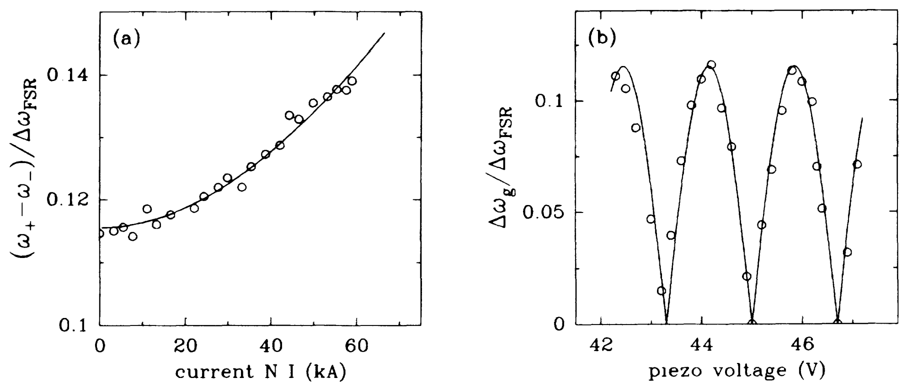

FIG. 4. (a) Dependence of the normalized doublet splitting $(\omega_+ - \omega_-)/\Delta\omega_{FSR}$ on the solenoid current NI, which is proportional to the effective rotation rate: $\Omega_{eff} = VNInc/mL$. The solid curve has been obtained with fit parameters $\gamma = 0.127$, $\alpha = 0.15$, and $V = 4.3 \times 10^{-6}$ rad/A. Note that a current $NI = 60$ kA corresponds to an effective rotation rate $\Omega_{eff} = 4.6$ rad/s. (b) Normalized band gap $\Delta\omega_g/\Delta\omega_{FSR}$ as a function of the voltage applied to the piezopositioner controlling the air gap. The width d of the air gap varies roughly in a linear way with this voltage.

spectrum (Fig. 2). The feeding fiber of the ring contains a polarization controller (not shown), which is set such that light entering the ring has circular polarization.[16]

Typical experimental spectra $I_T(kL, \Omega_{eff})$ and $I_R(kL, \Omega_{eff})$, obtained for maximized backscatter γ, are shown in Figs. 3(a)-3(d). For the stationary ring ($\Omega_{eff} \propto NI = 0$) the transmission and reflection spectra [Figs. 3(a) and 3(b)] are symmetric resonance doublets with a splitting $\Delta\omega_g = 2\pi \times 7$ MHz. At each resonance the cw component is directly excited by the incoming laser light, whereas the ccw component builds up as a result of constructive interference of scattered waves. The cw and ccw components together form a standing wave, which inside F has twisted linear polarization.[17] When the magnetic field is turned on ($\Omega_{eff} = 4.4$ rad/s), the doublet splitting increases and the transmission doublet becomes asymmetric [Fig. 3(c)], indicating the onset of running wave character. The reflection doublet remains symmetric and decreases in strength [Fig. 3(d)]. These experimental results are in good quantitative agreement with calculations based on a 1D coupled-mode theory[13] [Figs. 3(e)-3(h)]. The hyperbolic dependence of the doublet splitting $(\omega_+ - \omega_-)$ on Ω_{eff}, as expected from Eq. (1), is indeed confirmed by experiment [Fig. 4(a)]. A fit as shown in Figs. 3 and 4(a) results in $\gamma = 0.127$ (close to the maximum value of 0.131, based on Fresnel reflection), a round-trip intensity loss $\alpha = 0.15$ and $V = 4.3 \times 10^{-6}$ rad/A. The latter value is in good agreement with literature data ($V = 4.54 \times 10^{-6}$ rad/A).[18] Note that in our experiment $\alpha < \sqrt{\gamma}$, a condition that should be met in order to have sufficient finesse to resolve the forbidden gap.[13] Provided that $\gamma \ll 1$, the width of the forbidden gap should satisfy $\Delta\omega_g \propto \sqrt{\gamma} \propto |\sin 2\pi d/\lambda|$, a dependence confirmed by experiment [Fig. 4(b)].

In conclusion, we have demonstrated the existence of a photon band structure in an equivalent of the Sagnac interferometer with backscattering. The novelty of this type of photon band structure lies in the *macroscopic* nature of the periodicity involved, which distinguishes it from the well-known variety of photon band structures associated with the propagation of light in a medium which has periodic structure on a *microscopic* scale.[7,8] In the latter case the period is on the order of 10^{-6} m, whereas in our case the period is the ring's length, i.e., several meters. This macroscopic nature allows easy manipulation of basic parameters of the photon band structure; we therefore expect to open a rich new field. As a first example, the vector character (polarization) of the photon band structure may now be studied; in electronic band structures the vector character (electron spin) is often disregarded. In preliminary experiments we have already observed a rich phenomenology of crossings and anticrossings, induced by adjustable birefringement elements at various positions along the ring. A theoretical analysis is forthcoming.[13] As a second example, we have started experiments to observe transient effects in the photon band structure, such as Bloch oscillations and Zener tunneling.[5]

We thank E. R. Eliel for stimulating discussions and J. S. M. Kuyper for help with the experiments. This work is part of the research program of the Foundation for Fundamental Research on Matter and was made possible by financial support from the Netherlands Organization for Scientific Research.

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[11]Note that the phenomenon should be distinguished from that of frequency locking of a ring-laser gyroscope at low Ω; the latter effect is due to backscattering-induced injection locking of two counterpropagating waves in a gain medium and does not lead to forbidden frequency gaps. See, e.g., A. E. Sigeman, *Lasers* (University Science Books, Mill Valley, 1986), Sect. 29.6.

[12]The manufacturer specifies a polarization beat length of at least 5 m.

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[15]This polarization controller is adjusted to compensate all other birefringence in the fiber ring by use of the following procedure, while observing the spectra $I_R(kL)$ and $I_T(kL)$. The backscattering γ is set to zero, so that during each piezoscan of the ring over its free spectral range, two cw polarization eigenmodes are excited. By adjusting the polarization controller these two eigenmodes are made to coincide, indicating vanishing round-trip birefringence (linear as well as circular).

[16]To check this, backscattering and magnetic field are set to zero, so that the eigenmodes are running waves (cw), which are twofold degenerate, because the round-trip birefringence vanishes. This degeneracy is subsequently destroyed by turning on the magnetic field, leaving two cw eigenmodes, circularly polarized inside F (σ^+ and σ^-). The polarization controller in the feeding fiber is set such that only one of these (either σ^+ or σ^-) is excited.

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