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Tuneable Interferometric Bandpass and Bandstop Filters for Terahertz Applications

Otto Schwelb and István Frigyes

***Abstract* – Numerically simulated performance of a new type of tuneable bandstop and bandpass filter is presented. The filters use 2×2 couplers loaded by discontinuity-assisted ring resonators (DARR). The bandstop filter consists of one or several cascaded DARRs. Two bandstop filters separated by a cavity make up the bandpass filter. Tuning is achieved by varying the geometrical or material parameters of the ring resonators or the cavity. Alternatively, when the device is used as a sensor, environmental conditions are monitored by their detuning effect. Selectivity and tuning range are controlled by the coupling coefficient of the couplers, by the circumference of the rings and by the reflection coefficient of the discontinuities. The effects of coupler and waveguide loss have also been investigated.**

I. Introduction

Quasi-optic tuneable bandstop and bandpass filters with bandwidths from the KHz to GHz range are key components in measurement, telecommunication and sensing. Analytical investigations show that a 2×2 coupler (lumped element or distributed parameter type) loaded by a ring resonator that incorporates a controlled amount of small reflective discontinuity can be a very effective bandstop filter subject to the strength of coupling. Using this circuit as a basic building block (BBB) we investigated several bandstop and bandpass filter configurations with remarkably selective properties. The bandstop filter, effectively a highly reflective composite mirror, is fabricated from one or several cascaded BBBs. The bandpass filter consists of two such mirrors, separated by a cavity, much like a Fabry-Perot resonator. The discontinuity built into the ring resonator can be a mismatch or a short length of waveguide with material or geometric properties slightly different from that of the ring.

The results have been obtained from a computer program using a lumped element model for the couplers; neither the fabrication technology of the resonant ring nor that of the discontinuity is addressed since they strongly depend on the band of operation. Some of our simulations have been carried out at 3THz, others at 194THz.

Tuning of the bandstop filter is achieved by modulating the parameters of the ring or that of the discontinuity. Tuning of the bandpass filter requires variation of the phase delay in the cavity between the mirrors. To obtain such a phase delay variation either the length or the refractive index of the cavity must be adjusted. Among the means to produce this adjustment are micromechanical, piezoelectric, electrooptic and thermal. Conversely, environmental conditions can be monitored by their detuning effect. The technologies of tuning and modulation have not been here considered.

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II. Discontinuity-Assisted Ring Resonator

The BBB of the filter is a 2×2 coupler loaded by a DARR as shown in Fig.1, where K is the power coupling coefficient of the coupler, γ its fractional power loss and r is the reflection coefficient of the discontinuity.

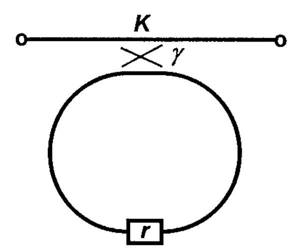

Fig.1. The basic building block of the filters: a 2×2 coupler loaded by a discontinuity-assisted ring resonator.

It is apparent that without the reflective discontinuity the circuit has an all-pass characteristic [1], i.e., the magnitude of the transmitted intensity in a lossless device is unity, and therefore without the reflective discontinuity the lossless circuit cannot be used as a frequency filter. (A lossy circuit without a discontinuity will still not reflect power back to the input, but its transmission will exhibit a notch near resonance.) Indeed, by exploiting the frequency dependency of its transmission *phase*, this circuit can be used as a group delay compensator [2].

While its reflectivity must be carefully controlled, the nature of the discontinuity embedded in the resonant ring is immaterial. It can consist of a small mismatch, a single step-index dielectric layer, a short shallow grating, etc. We assume a symmetric discontinuity, which is most conveniently represented by the scattering matrix [3]

$$S_d = \begin{bmatrix} r & jt \\ jt & r \end{bmatrix} \qquad (1)$$

where $t = \sqrt{1-r^2}$ is the transmission coefficient of the discontinuity. In practice the reflection coefficient is small, in the order of 10^{-4} to 10^{-1} therefore, to obtain a high Q resonance, the power coupling coefficient K must be small as well, usually between 40dB and 10dB. Note also that it makes no difference for the operation of the DARR where inside the ring the discontinuity is located. Using a conventional model for the coupler [4] the two distinct elements of the scattering matrix of the BBB are

$$S_{11} = \frac{-a^2 rK \exp(jkL)}{\exp(j2kL) - a^2(1-K) - j2at\sqrt{1-K}\exp(jkL)} \quad (2)$$

and

$$S_{21} = a\frac{\left[\exp(j2kL) - a^2\right]\sqrt{1-K} - jat(2-K)\exp(jkL)}{\exp(j2kL) - a^2(1-K) - j2at\sqrt{1-K}\exp(jkL)} \quad (3)$$

where k is the wavenumber, L is the physical length of the ring and $a = (1-\gamma)^{1/2}$ is the amplitude loss coefficient of the coupler (γ is the fractional power loss).

Equations (2) and (3) reveal that the BBB is a bandstop filter whose behaviour is subject to the value chosen for K. Fig.2 depicts the wave intensity transmitted through the BBB as a function of detuning from the design frequency and as a function of K. (To convert from detuning to frequency multiply by c the free space velocity of light in mm/s.) The figure shows that at design frequency there is a critical value for K, denoted by K_c, where the transfer intensity is zero. For $K < K_c$ the resonator is undercoupled, showing two minima, increasingly separated as the value of K decreases. For $K > K_c$ the resonator is overcoupled showing one minimum which becomes increasingly shallow as the value of K rises. The relationship between K_c and r is:

$$K_c = \frac{2r}{1+r} \cong 2r \quad (4)$$

Important to notice is the second derivative of I_{21} with respect to frequency at centre wavelength. For an undercoupled DARR this is negative, whereas for an overcoupled DARR it is positive.

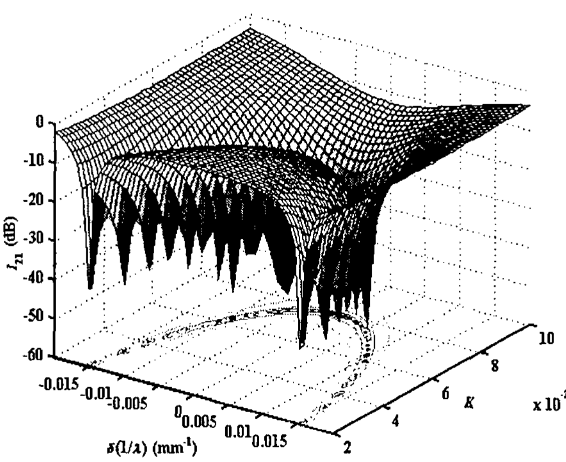

Fig.2. Intensity transfer through the BBB as a function of detuning and power coupling coefficient.

III. BANDSTOP FILTER CONSTRUCTION

Although the BBB offers large rejection levels, its skirt selectivity is not sufficiently steep. This can be improved upon by cascading several BBBs, separated by lengths of waveguides. To reinforce the reflection from each unit, the phase delay between consecutive BBBs must be such as to cause constructive interference at the entrance port, much like in the case of reflected wavelets from each element of a Bragg grating in the stopband region [5]. Such constructive interference is achieved when the length of the waveguide separating the BBBs is an integral multiple of $\ell_\pi = \lambda_0/2n_e$, where λ_0 is the design wavelength and n_e the effective index of the guide. Fig.3 shows the transfer characteristics of N cascaded, undercoupled, identical BBBs. The bandwidth of the stopband of this composite mirror is proportional to r and inversely proportional to L_{eff} the effective length of the resonator (length×effective index):

$$\Delta f \cong \frac{cr}{\pi L_{eff}} \quad (5)$$

This is in accordance with the fact that the group delay through the composite mirror at λ_0 is proportional to L_{eff} and inversely proportional to r. The performance characteristics of the composite mirror in the stopband region, including the group delay, are similar to those of a long Bragg grating [6]. By cascading undercoupled and overcoupled building blocks square well (flat bottom) stopband characteristics can be obtained.

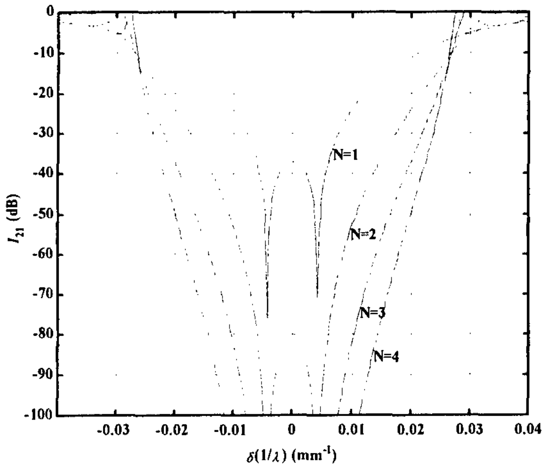

Fig.3. Intensity transfer as a function of detuning through N cascaded, undercoupled, identical BBBs.

IV. FABRY-PEROT TYPE BANDPASS FILTER

Since the transmission characteristic of a cascaded BBB is analogous to a composite mirror, one can build a Fabry-Perot type bandpass filter by inserting a waveguide between two identical chains of BBBs as shown in Fig.4.

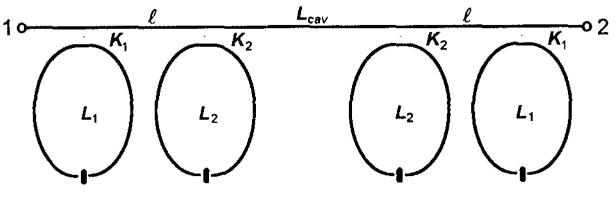

Fig.4. Fabry-Perot type bandpass filter consisting of two composite mirrors separated by a cavity.

If the length of the cavity (or defect, as it is sometimes called) is

$$L_{cav,n} = (n_{cav} + \tfrac{1}{2})\frac{\lambda_0}{2n_{eff}}, \quad n_{cav} \text{ integer} \qquad (6)$$

then the passband peak will fall in the middle of the stopband of the composite mirrors, i.e., on the design frequency. The maximum *continuous* tuning range within the mirror stopband, obtained by varying the cavity length is approximately $\Delta L_{cav} = 0.5\ell_\pi$, where ΔL_{cav} is the change in the physical length. Larger values of ΔL_{cav} to obtain the same tuning range can be realised by jumping from one n_{cav} to another, as implied by (6). When the cavity is tuned by refractive index variation the maximum tuning range is $\Delta n_e = n_e/(2n_{cav}+1)$. In either scheme the total phase delay while tuning the cavity from end of its range to the other is approximately $\Delta\phi = \pi/2$. Fig.5 shows the intensity transfer characteristics of the filter, centred at 3THz, using composite mirrors built with three unit cells having coupling coefficients $K_1=K_3=0.00103$ (29.9dB) and $K_2=0.00255$ (25.94dB), the reflection coefficient was $r = 0.001$. The solid lines are the bandpass curves corresponding to cavity lengths $L_{cav} = 100.58\ell_\pi$, $100.50\ell_\pi$ and $100.42\ell_\pi$, respectively, the dash-dotted line marks the flat-floor bandstop of the mirrors. The passband peaks rise from this floor; the lower the floor level the narrower are the passbands. A flat floor insures a constant bandwidth across the tuning range.

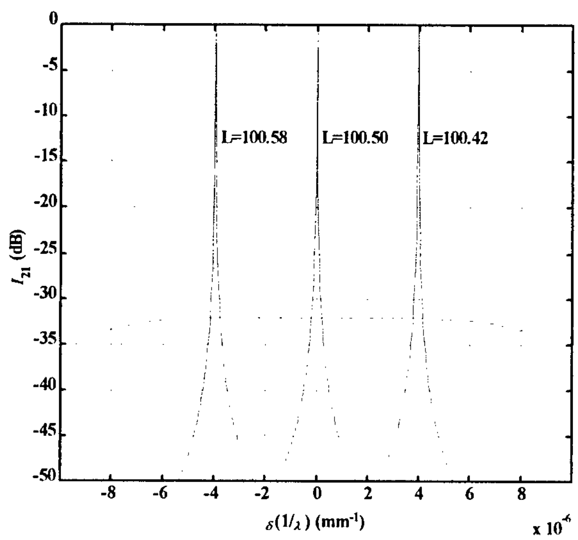

Fig.5. Transmission intensity as a function of detuning for three cavity lengths. The dash-dotted curve refers to the bandstop filters that comprise the mirrors.

V. THE EFFECT OF LOSS

The finite bandwidth and the corresponding finite Q of the bandpass filter fabricated with lossless components is an indication that the composite mirrors are partially transmitting. The smaller this transmission is, the larger is the Q:

$$Q = 2\pi \frac{L_{eff}}{\lambda_0 r I_{21}} \qquad (7)$$

where I_{21} is the numerical value of the floor level transmission. Losses reduce the peak transmission and broaden the resonance curve.

In interferometric circuits one encounters coupler loss and ring resonator waveguide loss. These have demonstrably equivalent effect on the transmission and group delay characteristics of the filter. In comparison, waveguide losses in the connecting guides and in the cavity have insignificant effect on transmission. This is because a resonant ring 'magnifies' its losses (as well as its transmission group delay) proportional to $1/K$, usually a large number. Fig.6 is a surface plot of the bandpass peak in the vicinity of band centre as a function of fractional coupler loss. The plot shows the rapid deterioration of the passband characteristic with increasing γ. The parameters used to obtain Fig.6 are the same as those for Fig.5. An identical plot is obtained when instead of increasing γ from 0 to γ_{max}, the waveguide attenuation coefficient α is increased from 0 to $\alpha_{max} = \gamma_{max}/2L$, where α is in Np/mm and the length of the ring is in mm. Respecting the above law of equivalence between attenuation coefficient and fractional power loss, the two loss mechanisms are additive.

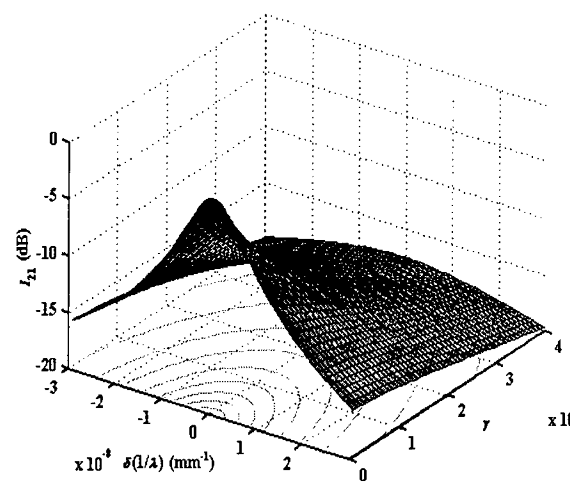

Fig.6. Surface plot of the intensity transfer as a function of detuning and fractional coupler loss.

Transmission levels of lossy filters also depend on K/K_c and the number of BBBs in the composite mirrors. This is illustrated in Fig.7, showing the transmitted intensity of bandpass filters at 3THz design frequency as a function of the relative coupling coefficient. The solid (dash-dotted) lines refer to $\gamma = 1\times10^{-6}$ ($\gamma = 1\times10^{-5}$), N represents the number of identical BBBs in each mirror and $\alpha = 0$. Observe how the transmission level for a given setting of γ drops as K approaches K_c and how sensitive this transmission is to N. The acute sensitivity of interferometric circuits based on resonant rings to loss might require inclusion of active elements that can provide the small amount of gain necessary to offset the losses.

VI. DESIGN PROCEDURE

The fundamental parameters and technological constraints given when designing a tuneable ring resonator based terahertz filter are: the centre wavelength, the tuning range, the stopband or passband width, the effective refractive index of the guides and the minimum, or desirable length (circumference) of the rings. The minimum free spectral range (FSR) might also be specified, but its value is subject to the minimum ring radius.

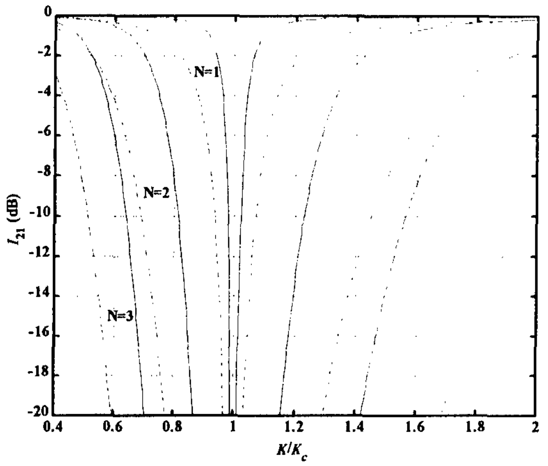

Fig.7. Transmission intensity vs. relative coupling coefficient of lossy bandpass filters using N identical BBBs in each mirror.

From (5) one can determine the reflection coefficient of the discontinuity r. When the discontinuity is a single defect layer, its refractive index n_a and length l_a are determined from

$$r = \left|\rho \frac{1-\exp(-j2k_a l_a)}{1-\rho^2 \exp(-j2k_a l_a)}\right| \tag{8}$$

where k_a is the wavenumber in the defect layer and

$$\rho = \frac{n_a - n_{eff}}{n_a + n_{eff}} \tag{9}$$

assuming $n_a > n_{eff}$. The maximum value of r provided by (8) is

$$r_{max} = \frac{2\rho}{1+\rho^2} \tag{10}$$

and the relative index and length of the defect layer are, respectively

$$\frac{n_a}{n_{eff}} = \sqrt{\frac{1+r_{max}}{1-r_{max}}} \text{ and } l_a = (2N+1)\frac{\lambda_0}{4n_{eff}}\sqrt{\frac{1-r_{max}}{1+r_{max}}} \tag{11}$$

With the stopband width and the design wavelength we first determine the Q, then substituting the value of r and Q into (7) the floor level transmission intensity of the square well bandstop characteristics is computed. Next the coupling coefficients are adjusted to meet this requirement. The number of DARR loaded couplers is determined by the required filter skirt selectivity (and loss considerations), while the length of the guide separating the couplers within the composite mirror must be an integral multiple of ℓ_π. The length of the cavity at centre frequency is determined by (6). When the cavity is tuned via index modulation, increasing the value of n_{cav}, as indicated above, can reduce the modulation depth necessary to tune through the stopband. The transmission and reflection characteristics of the bilaterally symmetric Fabry-Perot type bandpass filter are obtained from its scattering parameters:

$$S_{BP11} = S_{M11}\left[1+\frac{S_{M21}^2 e^{-j2kL_{cav}}}{1-S_{M11}^2 e^{-j2kL_{cav}}}\right] \tag{12}$$

and

$$S_{BP21} = \frac{S_{M21}^2 e^{-jkL_{cav}}}{1-S_{M11}^2 e^{-j2kL_{cav}}} \tag{13}$$

where S_{M11} and S_{M21} are the scattering parameters of the composite mirrors on either side of the cavity. A computer code to follow through these steps has been developed.

VII. CONCLUSIONS

Simulated characteristics of a novel, tuneable bandstop and bandpass filter have been described. The bandstop filter, fabricated with one or several cascaded 2×2 couplers loaded by discontinuity-assisted ring resonators (DARR) is regarded as a composite mirror. The bandpass filter consists of two such mirrors in a Fabry-Perot configuration. The bandwidth is adjustable and can be made arbitrarily small. The effect of the parameters controlling the tuning range and the passband width, as well as the effect of waveguide and coupler loss has been investigated. A detailed design procedure has been described. The technological aspects of device fabrication and tuning have not been addressed.

ACKNOWLEDGMENT

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