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EXPERIMENTAL EXPLORATION OF THE LIMITS OF ACHIEVABLE Q OF GROOV--ETC(U)
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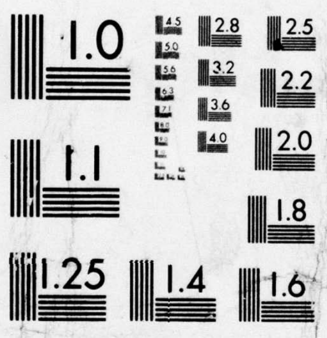

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EXPERIMENTAL EXPLORATION OF THE LIMITS OF ACHIEVABLE Q OF GROOVED SURFACE-WAVE RESONATORS*

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ABSTRACT An important basic question that remains to be answered for the surface-wave resonator is that of maximum achievable Q. Intrinsic material loss imposes a limit of $Q \approx 10^5$ at 150 MHz on $LiNbO_3$ and quartz. However, devices produced to date have been limited by grating reflection loss to $Q \approx 20{,}000$. This paper compares two alternative approaches to the problem of minimizing the grating reflection loss and hence maximizing the Q of the grooved Fabry-Perot resonator. In one approach, the number of elements (grooves) in the reflecting arrays is modest, and increasing array reflectivity (and hence Q) is obtained by increasing the element reflectivity (deepening the grooves). Experimental measurements show that Q can be increased in this way until a groove depth of roughly 0.025 λ (or a step reflectivity of about 1%) is attained on a 300-groove YZ $LiNbO_3$ resonator, at which point excessive losses due to bulk-wave scattering preclude the existence of a resonance. In the second approach, the element reflectivity (groove depth) is kept at a minimum and increasing reflectivity and Q are obtained by increasing the number of elements in the array. In either approach, element reflectivity is increased by a closer control of groove width-to-period ratio to values of 0.5 or less. Measurements of Q for various devices on $LiNbO_3$ and ST quartz are compared with theory. In addition, the maximum Q values measured will be compared with the theoretical maximum Q's set by intrinsic material losses.

Introduction

Surface-wave resonators for the lower UHF range are relatively easy to make, and Q values up to ten thousand or so can be obtained without much difficulty. For higher Q's, however, a number of different loss mechanisms, all small, can begin to limit the achievable Q, and greater care is necessary to minimize these losses. To our knowledge, the highest Q reported to date is approximatley 20,000 at 150 MHz on ST quartz. Such Q's are quite adequate for many applications, and simple filter networks using such resonators have been demonstrated at several laboratories.

Last year at this conference[1], and more recently at the Annual Frequency Control Symposium[2], we presented a theoretical assessment of the limits of achievable Q imposed by viscous and air-loading losses on the two commonly used substrates of $LiNbO_3$ and ST quartz. This assessment is summarized in Fig. 1, which shows that intrinsic material loss imposes a ceiling on Q of the order of 10^5 at 150 MHz on $LiNbO_3$ and ST quartz. (In the latter case, evacuation is also required to reach 10^5.)

In the present paper, we shall review the results of an experimental investigation into the feasibility of attaining the above limits.

Discussion

In order to understand the experiments performed, it will be helpful to first review the various loss mechanisms in a resonator, a schematic of which is shown in Fig. 2.

For the purposes of studying the loss processes in the intrinsic cavity, unperturbed by the presence of coupling transducers, we have confined our attention to the two-port configuration shown on the right. The various sources of loss, and the Q associated with each form of loss, in such a resonator are summarized in Table I. Q_L is the loaded Q of the cavity due to all sources of loss, and is related to various other Q's by the usual sum of inverse Q's. Q_m is associated

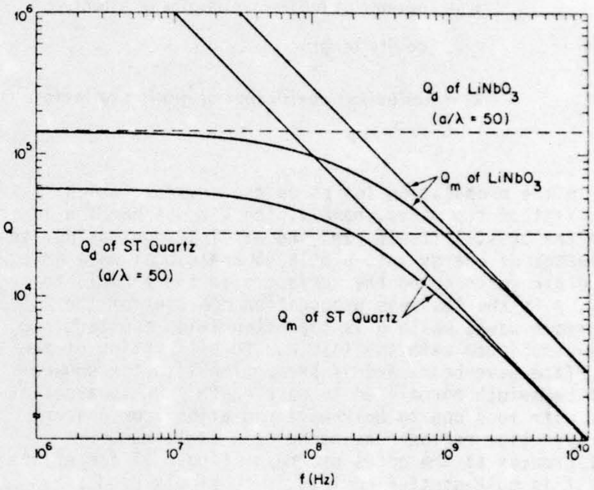

Fig. 1 Material and diffraction Q's for Y-Z $LiNbO_3$ and ST-quartz. Curved and straight lines for Q_m correspond to propagation loss with and without air loading, respectively.

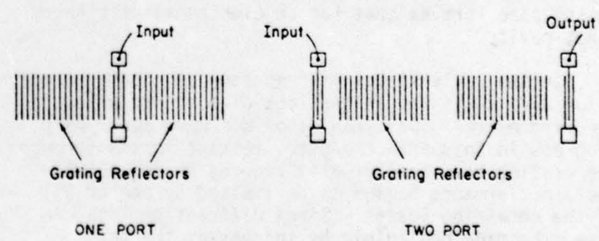

Fig. 2 Typical resonator configurations.

*This work was sponsored by the Department of the Air Force.
1975 Ultrasonics Symposium Proceedings, IEEE Cat. #75 CHO 994-4SU.

Table I

$$\frac{1}{Q_L} = \frac{1}{Q_m} + \frac{1}{Q_d} + \frac{1}{Q_b} + \frac{1}{Q_r}$$

- Q_L = *loaded Q*
- Q_m = *material Q* $= \frac{\beta}{2\alpha}$
- Q_d = *diffraction Q* $\sim (\frac{a}{\lambda})^2$ (*a = beam width*)
- Q_b = *bulk-scattering Q* $= \frac{\beta L_{eff}}{2A}$

  A = *attenuation due to bulk-scattering loss at grating edge*
- Q_r = *radiation Q* $= \frac{n\pi}{1 - R^2}$

  n = *number of half-wavelengths in effective cavity length*

  R = *reflection coefficient of grating reflector.*

with the propagation losses on the crystal, which consist of two parts, namely, the viscous damping loss in the crystal itself, and the air-loading loss due to leakage of energy into a bulk compressional wave in the air surrounding the surface. In the formula for Q_m, β is the lossless propagation constant of the surface wave, while α is the attenuation constant. Q_d is associated with the loss due to diffraction of the surface-wave beam, and is proportional to the square of beamwidth normalized to wavelength. Q_b is associated with loss due to bulk-wave radiation from a short interaction region consisting of a small number of grooves at the edges of the grating. If the effect of this bulk-scattering loss is to simply produce an attenuation of the form $e^{-A} \simeq 1-A$ ($A \ll 1$) in the incident surface wave, without any other effects, then it can be shown that a (bulk wave) Q_b can be defined as shown in the Table, where L_{eff} is the effective length of the cavity[2,3], and is assumed to be large in comparison to the interaction region. Finally, Q_r is the radiation Q associated with leakage through the imperfectly-reflecting gratings, and can be expressed in the same form as that for an electromagnetic Fabry-Perot cavity.

In the early stages of resonator development, the major difficulty lay in the lack of a strongly reflecting mirror, i.e., radiation Q's were low. With progress in this area, however, leakage losses through the grating have been greatly reduced to the point where performance begins to be limited by one or all of the remaining losses. Since diffraction loss can always be made negligible by increasing the beam width, the challenge in reaching the material Q lies in the design of a grating which minimizes leakage loss without incurring significant bulk-scattering loss at the grating edges.

In our first approach to the problem of minimizing leakage loss through the reflectors, we employed gratings containing a modest number of grooves and attempted to increase the grating reflectivity by deepening the grooves. In the second approach, groove depths were kept at a minimum while the number of grooves was greatly increased.

Independent of the particular approach adopted, the reflectivity of a groove, and hence the grating, is maximized by close control of width-to-period ratio to values of 0.5 or less. Since the variation of width-to-period ratio does not incur any additional bulk-scattering losses, it is important to optimize the array in terms of this parameter. As we have noted on previous occasions[1,2], a variation of 10% in the width-to-period ratio (equivalent to 20% in the previously used width-to-space ratio) results in a factor of 2 change in the radiation Q. Because of the importance of this point, we shall briefly examine the reason behind the sensitivity of Q_r on groove width. As shown in an earlier work[4], the reflection of a surface wave from a step consists of two contributions. The first is due to an impedance mismatch and is linear in groove depth. The second is due to stored energy and is quadratic in groove depth. Taken together, they give rise to a groove reflection coefficient Γ_g which may be expressed as follows:

$$|\Gamma_g| = C_1\left(\frac{h}{\lambda}\right) \sin 2\pi\frac{w}{\lambda} + C_2 \left(\frac{h}{\lambda}\right)^2 \cos 2\pi\frac{w}{\lambda} \qquad (1)$$

where C_1 and C_2 are constants appropriate to a given material, h and w are the groove depth and width, respectively, and λ is the surface-wave wavelength. In the vicinity of the grating stop-band, and hence resonance, we have $\lambda \simeq 2d$, so that eq. (1) may be written in the form:

$$|\Gamma_g| = C_1 \left(\frac{h}{\lambda}\right) \sin \pi\frac{w}{d} + C_2 \left(\frac{h}{\lambda}\right)^2 \cos \pi\frac{w}{d} \qquad (2)$$

For a typical cose of $h/\lambda = 0.01$ and $w/d = 0.55$, on $LiNbO_3$ ($C_1 = 0.67$, $C_2 = 42$), we have $|\Gamma_g| = 0.0067 - 0.00066$, and the stored energy term is seen to reduce the impedance mismatch term by 10%. This is almost an order of magnitude larger than the 1.3% change in the impedance-mismatch term due to a change in w/d from 0.5 to 0.55. It is also noted that the maximum value of $|\Gamma_g|$ does not occur at w/d = 0.5, as previously stated in error[2], but actually occurs for some value of w/d < 0.5, depending on the specific groove depth. Finally, it should be pointed out that energy storage also exists at the edges of other types of reflector, such as field-shorting strips (see Ref. 4 for measurement on $LiNbO_3$) or mass-loading strips. A similar sensitivity of $|\Gamma_g|$ and Q to w/d ratio should also be observed on resonators using those reflectors, and may in fact explain some of the discrepancy observed between measured values and those calculated neglecting the effect of energy storage.

Before turning to a description of the experimental results, we shall briefly review the transmission behavior through the two-port resonator of Fig. 2. This is done with the aid of Fig. 3, which shows the qualitative features of the transmission coefficient through the resonator (not including the effect of transducers) as a function of frequency. The two most important parameters in the measurement are 1) Q_L, the loaded Q, defined conventionally as the resonant frequency f_r divided by the half-power bandwidth, Δf, and 2) τ_r, the transmission coefficient through the resonator measured at resonance. For high-Q resonators, the latter can be shown to be related to the loaded and radiation Q's by the simple formula, $\tau_r = Q_L/Q_r$. A knowledge of τ_r thus permits other loss contributions to be distinguished from the leakage loss.

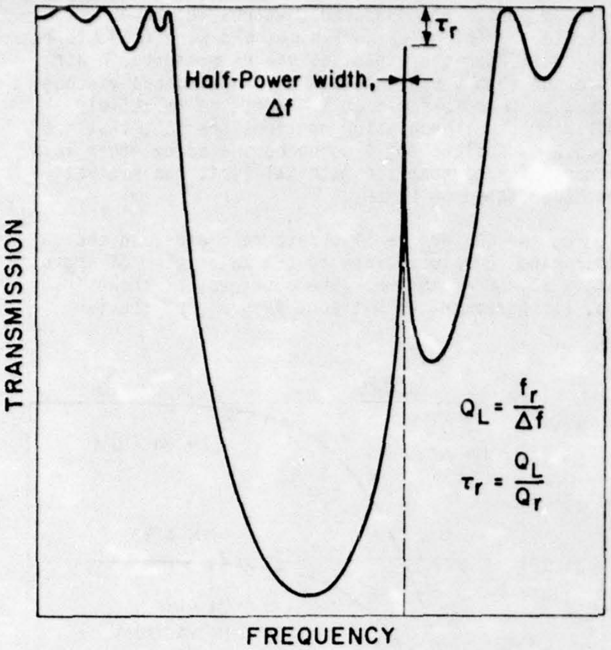

Fig. 3 Qualitatative behavior of transmission through resonator as a function of frequency.

Experiments

As mentioned in the introduction, two approaches to the problem of minimizing leakage loss through the gratings were investigated. These will be described below, and a comparison will be made of their relative merits.

1. Use of Deep Grooves

A modest number of 300 grooves per grating was employed in the fabrication of a series of eight 170 MHz resonators on Y-Z $LiNbO_3$. Starting with groove depths of 2000 Å ($h/\lambda_0 = 0.011$) for the resonator with the shallowest grating, each successive resonator was ion-beam etched deeper, with the deepest gratings being almost 1 μm in depth. The results of transmission tests through these resonators are shown in the photographs of Fig. 4. In order of increasing

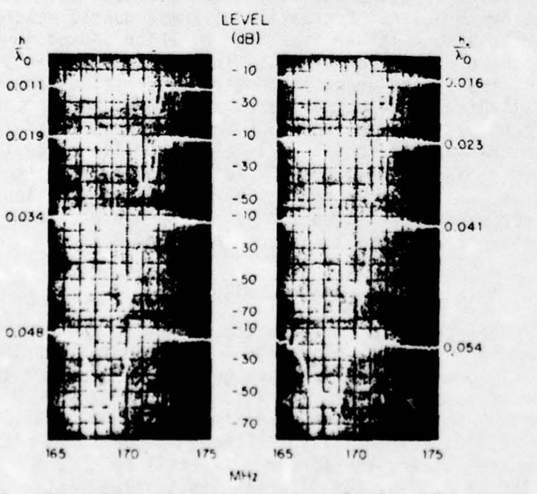

Fig. 4 Experimentally observed evolution of transmission through $LiNbO_3$ resonator at 170 MHz as a function of groove depth. Resonator has grooves per reflector and nominal 10λ cavity (measured between grating edges).

groove depth, the stop bands shift progressively downward and the resonances progressively upward relative to the stop-band center[2] as expected, and everything is well behaved for $h/\lambda_0 < 0.02$. For $h/\lambda_0 = 0.023$, a slight suggestion of "shoulders" is visible about 8 dB below the resonance peak, and by the time $h/\lambda_0 = 0.034$, the resonance peak has broken up into two distinct and closely spaced peaks. These peaks are still visible for $h/\lambda_0 = 0.041$, but beyond this depth, all trace of a resonance has vanished. It is also observed that the bottom of the stop band starts to become "hashy" for $h/\lambda_0 = 0.034$, presumably as a result of scattering into the bulk. Finally, the stop-band shape becomes progressively more asymmetric as groove depth increases. Based on the above observations, it is tentatively concluded that the degradation of the resonance at large values of h/λ is due to bulk-wave scattering, and this scattering imposes an upper limit of roughly 2.5% on the normalized groove depth, h/λ_0, which can effectively be employed in the 300 groove resonator. Beyond that limit, the resonance begins to "break up", and ultimately disappears completely. If, as conjectured, the major source of this bulk-wave loss occurs at the "front" of the gratings, immediately adjacent to the cavity region, then it may be possible to reduce this loss, and hence push back the depth limit, by gradually tapering the groove depth up to its final value over a certain number of grooves. A summary of the Q's measured in the 300-groove experiments is shown in Fig. 5, and it is apparent that the material Q of 70,000 at 170 MHz is still a long way away.

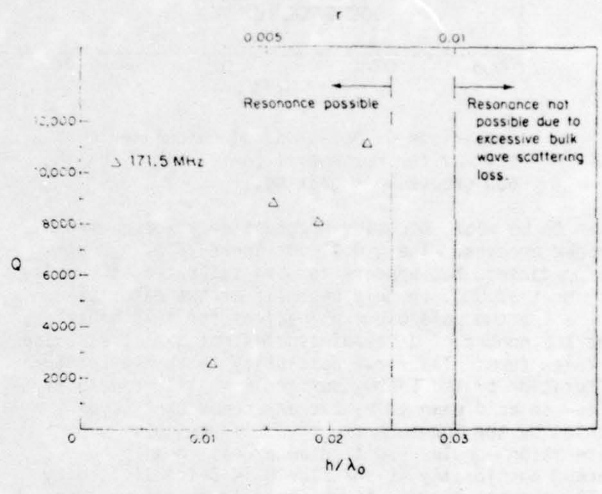

Fig. 5 Summary of measured Q's at 170 MHz and bulk-wave limit on groove depth for resonators on Y-Z $LiNbO_3$ having 300 grooves per grating.

In addition to the usual abscissa, h/λ_0, it is also of interest to add the abscissa, r, where the latter represents the reflection coefficient magnitude for a single step-discontinuity in the substrate surface. (For Y-Z $LiNbO_3$ $r \approx 0.33\ h/\lambda_0$.) From Fig. 5 the onset of the bulk-wave limit is seen to occur at a step reflectivity of roughly 1% for Y-Z $LiNbO_3$. This reflectivity of the elemental reflector at which the onset of the bulk-wave limit occurs may be viewed as a kind of figure of merit for the given reflector, and a comparison of various reflectors on this basis would be of interest.

2. Use of Many Grooves (Long Arrays)

In the second approach to the minimization of leakage loss, resonators were fabricated on Y-Z $LiNbO_3$

and ST quartz, having the much larger number of 600 shallow grooves per grating, with depth no greater than 1.5% of a wavelength. Measured results on the $LiNbO_3$ devices are summarized in Fig. 6, and compared with a theoretical prediction of the results, based upon a previously described model[1,2]. Agreement is

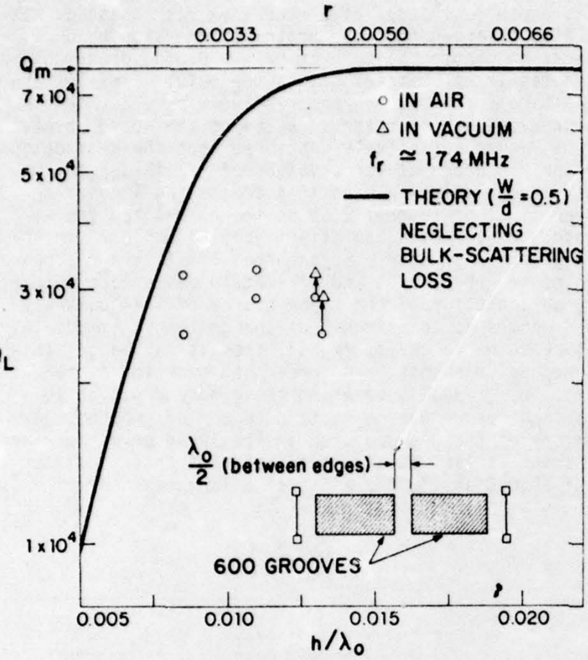

Fig. 6 Comparison of measured and calculated Q at 174 MHz for resonators on Y-Z $LiNbO_3$ having 600 grooves per grating.

seen to be poor, becoming progressively worse with deeper grooves. The Q does not increase with depth, as predicted, but appears to have saturated at a value of about 32,000, roughly one half of the material Q. There are two possible explanations for this behavior, but the number of data points does not permit a choice between them. The first possiblity is that a residual alteration of the $LiNbO_3$ surface may still remain even after an acid wash to remove any conducting layer caused by the ion-beam etching. If present, such alteration could result in an excess loss. The second possibility is that the Q is being limited by bulk-wave scattering, as observed in the 300-groove experiment. However, we note that the bulk-wave limit is now at much higher Q, as would be expected for the shallower grooves employed. It is important to appreciate the fact that the maximum groove depth usable in a resonator is a function of the number of grooves (reflectors) employed. With a large number of grooves, as in this experiment, Q_r can be very high for very shallow grooves, in which case the resonator becomes sensitive to the very small scattering losses. With fewer grooves, as in the 300-groove experiment, Q_r is not as high, or leakage losses are larger, so that small scattering losses are not as significant. Thus, deeper grooves can be used up to the point where the scattering loss again becomes significant in comparison to the leakage loss. The above considerations are consistent with the formula $Q_b = \beta L_{eff}/2A$, which implies that the bulk-wave limit on Q is higher for longer arrays of shallower grooves, for which L_{eff} is larger and A is smaller.

Two of the above $LiNbO_3$ resonators were also mounted in sealed brass packages and evacuated through a vacuum port. The measured Q values in vacuum are indicated by triangles in Fig. 6, and were found to be only some 20% higher than the values measured in air. Since the theory predicts the air-loading and viscous losses to be comparable at 174 MHz, the relatively small impact of evacuation confirms the fact that the viscous losses are still being dominated by other loss mechanisms, and that the material limit has not yet been approached on $LiNbO_3$.

On the 600-groove ST-quartz resonator, on the other hand, Q values close to the material Q of approximately 30,000 at 157 MHz were obtained, as shown in Fig. 7. Agreement with theory is good for the two

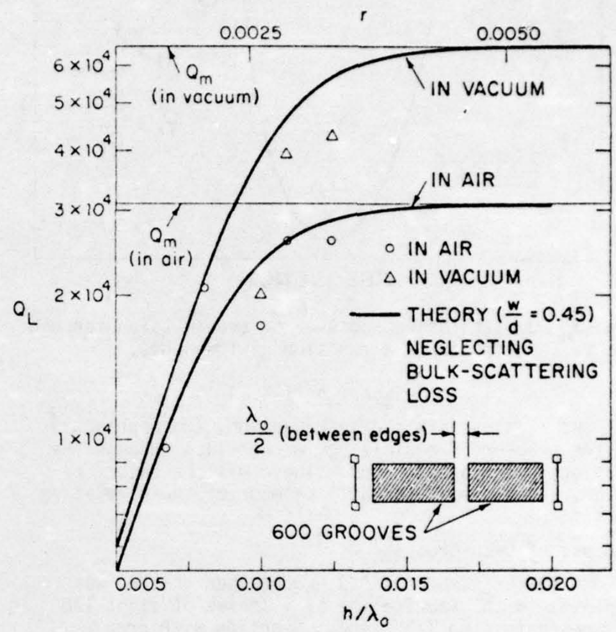

Fig. 7 Comparison of measured and calculated Q at 157 MHz for resonators on ST-quartz having 600 grooves per grating.

shallowest resonators, but begins to deteriorate for the deeper cases, presumably as a result of bulk-wave scattering again. Evacuation of these quartz resonators exerted a much larger impact on Q, which showed increases of the order of 72%. In the case of ST-quartz also, the theory predicts comparable contributions for air-loading and viscous losses at 157 MHz. The observed percentage increase in Q upon evacuation is consistent with the measured Q values in air which lie close to the material limit imposed by air-loading and viscous losses. Finally, we note that the transmission loss at resonance was in general larger than expected, consistent with the lower than expected Q's.

Conclusion

The results of the two approaches to the problem of minimizing grating leakage loss indicate that the use of long arrays of shallow grooves is superior to shorter arrays of deep grooves. At 174 MHz on $LiNbO_3$, the two approaches yielded maximum Q values of 33,000 and 11,000, respectively. Although three times higher than the latter, the former Q is still roughly a factor of 2 below the material limit, presumably because of scattering losses into the bulk at the grating edges. These should be reduceable to some extent by some form of depth tapering into the array. It is not clear, however, that such an effort is warranted for $LiNbO_3$ since its strong temperature

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(19) REPORT DOCUMENTATION PAGE

READ INSTRUCTIONS BEFORE COMPLETING FORM

1. REPORT NUMBER: (18) ESD-TR-76-260

2. GOVT ACCESSION NO.:

3. RECIPIENT'S CATALOG NUMBER:

4. TITLE (and Subtitle): (6) Experimental Exploration of the Limits of Achievable Q of Grooved Surface-Wave Resonators.

5. TYPE OF REPORT & PERIOD COVERED: (9) Journal Article,

6. PERFORMING ORG. REPORT NUMBER: (14) MS-4088

7. AUTHOR(s): (10) Li, Robert C. /Li, ~~Alusow~~, John A. /Alusow Williamson, Richard C. /Williamson

8. CONTRACT OR GRANT NUMBER(s): (15) F19628-73-C-0002

9. PERFORMING ORGANIZATION NAME AND ADDRESS: Lincoln Laboratory, M.I.T. P.O. Box 73 Lexington, MA 02173

10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS: 649L

11. CONTROLLING OFFICE NAME AND ADDRESS: Air Force Systems Command, USAF Andrews AFB Washington, DC 20331

12. REPORT DATE: (11) 22 Sep [redacted] 75

13. NUMBER OF PAGES: 5 (12) 6p.

14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office): Electronic Systems Division Hanscom Air Force Base Bedford, MA 01730

15. SECURITY CLASS. (of this report): UNCLASSIFIED

15a. DECLASSIFICATION DOWNGRADING SCHEDULE: n/a

16. DISTRIBUTION STATEMENT (of this Report)

Approved for public release; distribution unlimited.

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

1975 Ultrasonics Symposium Proceedings, IEEE Cat. #75, CHO 994-4SU

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Grooved surface-wave resonator Maximum Q Q losses

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

LiNBosub3 Lambda 100,000

An important basic question that remains to be answered for the surface-wave resonator is that of maximum achievable Q. Intrinsic material loss imposes a limit of Q ≈ 10^5 at 150 MHz on $LiNbO_3$ and quartz. However, devices produced to date have been limited by grating reflection loss to Q ≈ 20,000. This paper compares two alternative approaches to the problem of minimizing the grating reflection loss and hence maximizing the Q of the grooved Fabry-Perot resonator. In one approach, the number of elements (grooves) in the reflecting arrays is modest, and increasing array reflectivity (and hence Q) is obtained by increasing the element reflectivity (deepening the grooves). Experimental measurements show that Q can be increased in this way until a groove depth of roughly 0.025 λ (or a step reflectivity of about 1%) is attained on a 300-groove YZ $LiNbO_3$ resonator, at which point excessive losses due to bulk-wave scattering preclude the existence of a resonance. In the second approach, the element reflectivity (groove depth) is kept at a minimum and increasing reflectivity and Q are obtained by increasing the number of elements in the array. In either approach, element reflectivity is increased by a closer control of groove width-to-period ratio to values of 0.5 or less. Measurements of Q for various devices on $LiNbO_3$ and ST quartz are compared with theory. In addition, the maximum Q values measured will be compared with the theoretical maximum Q's set by intrinsic material losses.

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SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered) dependence limits its usefulness in narrow-band resonator applications.

Measurements on ST-quartz at 157 MHz using long arrays of shallow grooves yielded maximum Q values of 24,300 in air, very close to the material limit, as confirmed also by the large effect of evacuation. ST-quartz resonators with Q values near the material limit therefore appear to be achievable with the present technique of using long arrays of shallow grooves.

Acknowledgement

The authors are deeply indebted to many of their collleagues in the Microsound Group at Lincoln Laboratory, for a tremendous group effort which made the results of this paper available for this conference - to H. I. Smith for his design of experiments which led to the ability to control groove width-to-period ratio; N. Efremow and M. Dalomba for photolithography; W. T. Brogan and R. Eager for ion-beam etching; W. C. Kernan for metallization; and, especially, to R. Konieczka, who spent many hours of his own time working with us late into the morning hours on many occasions.

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