

Electrical Characterization of the SAW Filters

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1 SUMMARY OF SPECIFICATIONS

The following filters are examined: identifiers "B21" through "B25" and "C31" through "C35". The filters were manufactured according to the specifications listed in Table 1. The measured frequency-dependent attenuation values of the filters are shown in Figs. 1 and 2.

2 CENTER FREQUENCY AND PROPAGATION VELOCITY

The center frequency f_0 was determined from the measured data by calculating the mean value of the frequency values f_l and f_r , corresponding to the first zero crossing adjacent to f_0 in the transfer function $H(f)$ (see Fig. 1):

$$f_0 = \frac{f_l + f_r}{2}, \quad \sigma_{f_0} = \sqrt{(\sigma_{f_l}^2/4 + \sigma_{f_r}^2/4)}$$

The propagation velocity v of the surface waves on the LiNbO₃ substrate can then be calculated from the measured f_0 values using the wavelength λ_0 :

$$v = f_0 \lambda_0, \quad \sigma_v = \sqrt{(f_0 \sigma_{\lambda_0})^2 + (\lambda_0 \sigma_{f_0})^2}$$

Example As an example, these values are calculated from the measured data of filter identifier "C31", assuming $\sigma_{\lambda_0} = 0.1 \mu\text{m}$

C31, C32, C33, C34, C35		
Spacing d [μm]	L [μm]	Delay Time [μs]
2535	2718.3	0.697
2730	2913.3	0.747
2925	3108.3	0.797
3120	3303.3	0.847
3315	3498.3	0.897
Fundamental wavelength: $\lambda_0 = 37.6 \mu\text{m}$		
Fundamental frequency: $f_0 = 103.72 \text{ MHz}$		
Null-to-null bandwidth Δf : $0.2 f_0 = 0.2 v_s / \lambda_0 = 20.74 \text{ MHz}$		
Finger width a : $\lambda_0/8 = 4.7 \mu\text{m}$		
Number of finger pairs: 20		
B21, B22, B23, B24, B25		
Number of fingers N	L [μm]	Null-to-null bandwidth Δf [MHz]
32	3026.1	11.28
28	2988.5	12.90
24	2950.9	15.05
20	2913.3	18.06
18	2894.5	20.06
Fundamental wavelength: $\lambda_0 = 43.2 \mu\text{m}$		
Fundamental frequency: $f_0 = 90.28 \text{ MHz}$		
Spacing d : $2730 \mu\text{m}$		
Finger width a : $\lambda_0/8 = 5.4 \mu\text{m}$		

Table 1 | Design data of the SAW filters. Spacing d varies for filters "C3*". Number N of finger pairs varies for filters "B2*".

and $\sigma_{f_l} = \sigma_{f_r} = 0.5 \text{ MHz}$:

$$f_0 = \frac{92.2 + 113.1}{2} \text{ MHz} = 102.7 \text{ MHz}$$

$$\sigma_{f_0} = \sqrt{\frac{0.5^2}{4} + \frac{0.5^2}{4}} \text{ MHz} = 0.4 \text{ MHz}$$

$$v = 37.6 \mu\text{m} \cdot 102.7 \text{ MHz} = 3860 \text{ m/s}$$

$$\sigma_v = \sqrt{(102.7 \text{ MHz} \cdot 0.1 \mu\text{m})^2 + (37.6 \mu\text{m} \cdot 0.4 \text{ MHz})^2} = 18 \text{ m/s}$$

Analogous to the above calculations, the values of f_0 and v were determined for all filters and are listed in Table 2.

Discussion In Fig. 3, the mean values of the measured center frequencies f_0 of filters with identifiers "B2*", "C1*", "C2*", and "C3*" are plotted against the theoretically expected reciprocal wavelength. A linear regression yields a straight line that lies within the calculated uncertainties of f_0 . Its slope is given by

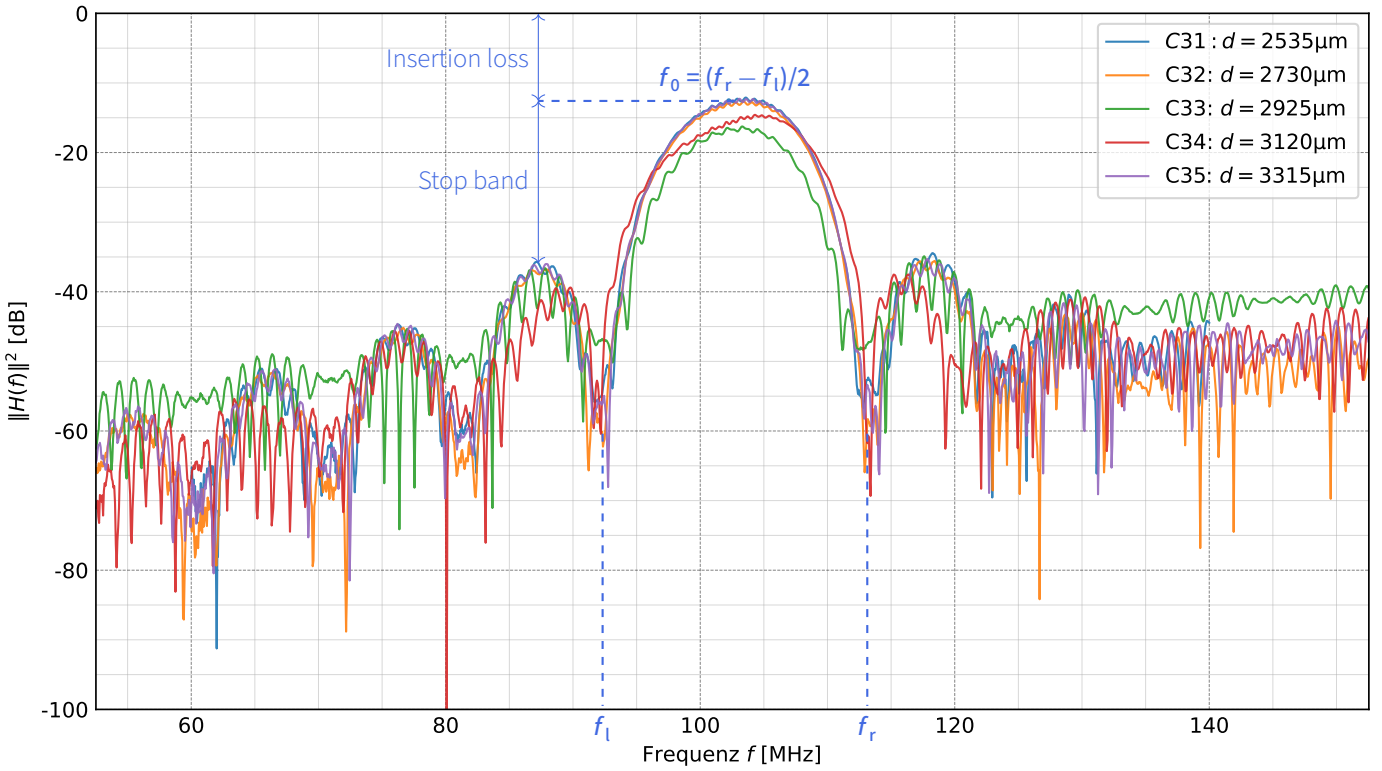


Figure 1 | Measured transfer function of filters "C31" through "C35". The determination of insertion loss and stop band for filter "C31" is shown.

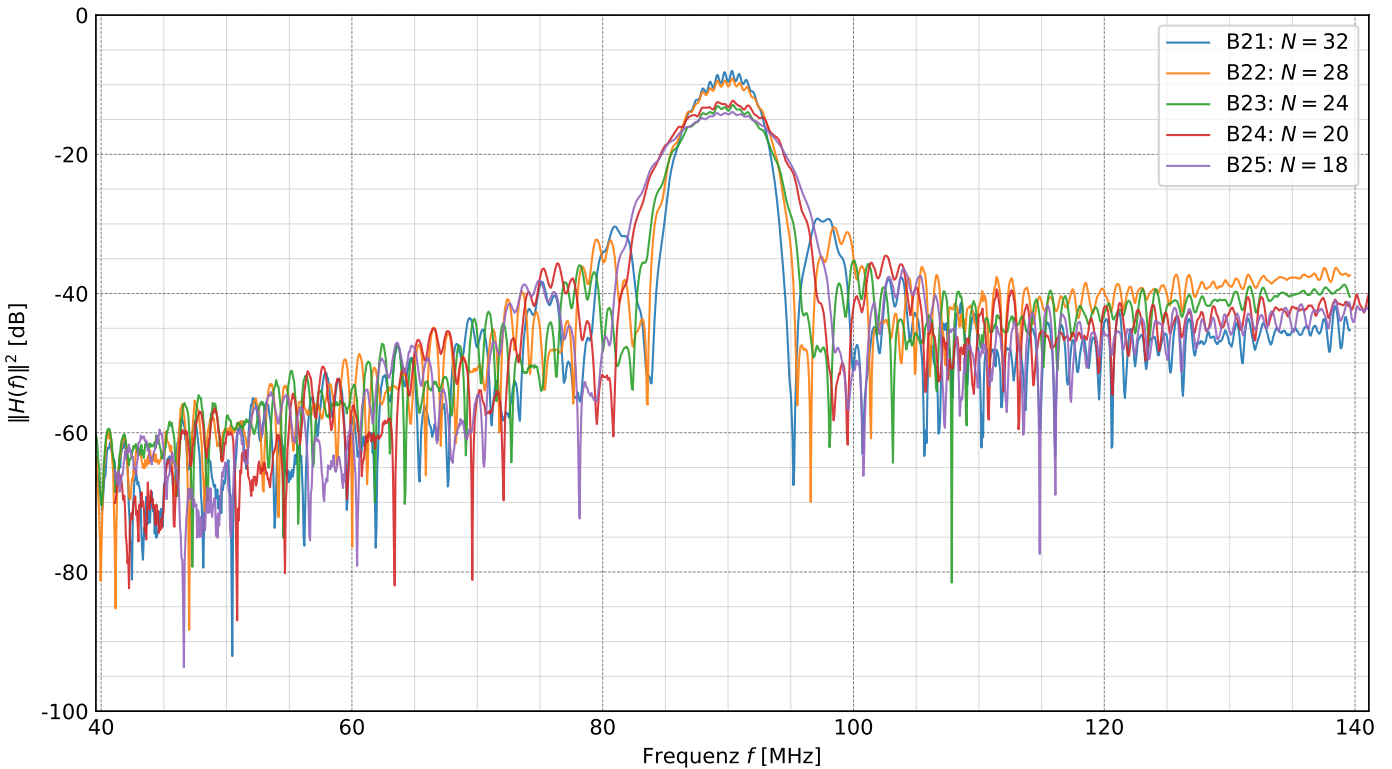


Figure 2 | Measured transfer function of filters "B21" through "B25".

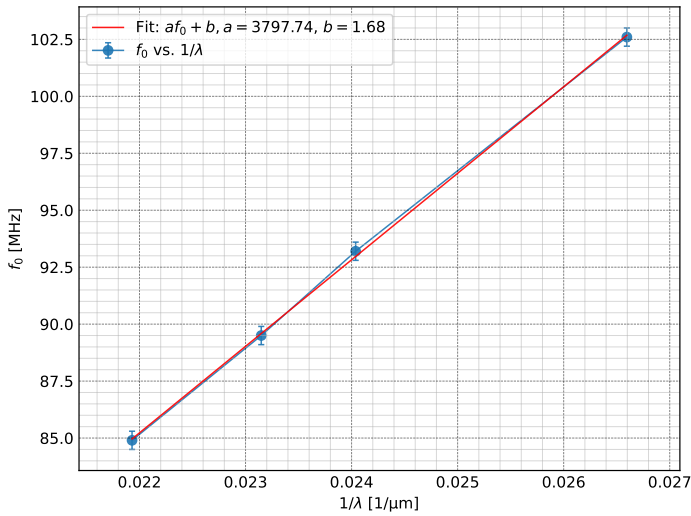
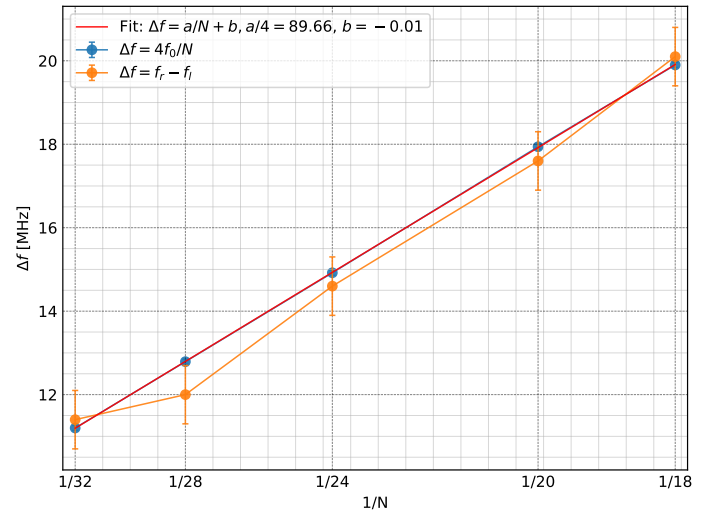
$a = 3797.74$ (m/s). This value corresponds to the propagation velocity of the waves on the LiNbO₃ substrate. The very small y-axis intercept of $b = 1.68$ indicates that this value is relatively precise. If this is compared with the mean value of the values in Table 2 (3865 m/s), a clear deviation is apparent. One possible reason is that in this case it is not generally valid to use $f_0 = (f_l + f_r)/2$, because f_0 is actually smaller than the mean of f_l and f_r . The

additional mass of the aluminum IDT structure should lower the theoretically expected frequency f_0 somewhat. Assuming that f_0 decreases by the same amount for all filters, one would expect the calculated velocity from the linear regression to remain unchanged even when f_0 varies. On the other hand, it is noticeable that the value $a = v = 3797.74$ m/s differs strongly from the literature value (approximately 3975 m/s, [1]). The reason is that the

Identifier	f_0 [MHz]	v [m/s]
"C31"	102.7(4)	3860(18)
"C32"	102.6(4)	3856(18)
"C33"	102.5(4)	3854(18)
"C34"	102.5(4)	3854(18)
"C35"	103.2(4)	3878(18)
"B21"	89.6(4)	3871(19)
"B22"	89.5(4)	3866(19)
"B23"	89.5(4)	3866(19)
"B24"	89.7(4)	3875(19)
"B25"	89.6(4)	3869(19)

Table 2 | Calculated values for f_0 and v from measured data.

Identifier	$4f_0/N$	Δf [MHz]	$f_r - f_l$
"C31"	20.53(8)		20.9(7)
"C32"	20.51(8)		21.5(7)
"C33"	20.50(8)		20.4(7)
"C34"	20.50(8)		21.8(7)
"C35"	20.63(8)		20.9(7)
"B21"	11.20(5)		11.4(7)
"B22"	12.79(5)		12.0(7)
"B23"	14.92(7)		14.6(7)
"B24"	17.94(8)		17.6(7)
"B25"	19.90(9)		20.1(7)

Table 3 | Calculated values for Δf from measured data.Figure 3 | Calculated f_0 from measurements of filters "B2*", "C1*", "C2*", and "C3*" plotted against $1/\lambda$.Figure 4 | Calculated values for Δf from measured data plotted against $1/N$.

substrate is not pure LiNbO₃.

3 NULL-TO-NULL BANDWIDTH

The null-to-null bandwidth Δf can be calculated from the difference between f_r and f_l :

$$\Delta f = f_r - f_l, \quad \sigma_{\Delta f} = \sqrt{\sigma_{f_l}^2 + \sigma_{f_r}^2}$$

The theoretically expected value can be calculated using the previously determined value for f_0 :

$$\Delta f = \frac{4f_0}{N}, \quad \sigma_{\Delta f} = \frac{4}{N}\sigma_{f_0}$$

Example As an example, these values are calculated from the measured data of filter identifier "C31":

$$\Delta f = 113.1 \text{ MHz} - 92.2 \text{ MHz} = 20.9 \text{ MHz}$$

$$\sigma_{\Delta f} = \sqrt{0.5^2 + 0.5^2} \text{ MHz} = 0.7 \text{ MHz}$$

$$\Delta f_{\text{theor.}} = \frac{4 \cdot 102.7}{20} \text{ MHz} = 20.53 \text{ MHz}$$

$$\sigma_{\Delta f_{\text{theor.}}} = \frac{4}{20} 0.4 \text{ MHz} = 0.08 \text{ MHz}$$

Analogous to the calculations above, the values of Δf for all filters were determined and are listed in Table 3.

Discussion In Fig. 4, the Δf values from Table 3 for filters "B21" through "B25" are plotted against the corresponding reciprocal of the number of finger pairs. It is apparent that the Δf values calculated from the measured data via the theoretical formula lie very well on a straight line. The slope of the linear regression yields $a/4 = f_0 = 89.66$ MHz, which corresponds to the center frequency of the filters. This value is very precise because the y-axis intercept obtained from the regression is nearly zero. It can also be seen that the values obtained from the difference of the zero crossings were determined within the limits of their accuracy.

4 DETERMINATION OF L

The length L can be measured indirectly by measuring two frequencies f_1 and f_2 that differ by a phase shift $\Delta\varphi = 2\pi$:

$$\varphi = 2\pi f \frac{L}{v}$$

$$\frac{\Delta\varphi}{\Delta f} = 2\pi \frac{L}{v}$$

$$\Delta\varphi = 2\pi, v = \bar{v}, \Delta f = f_2 - f_1$$

$$\Rightarrow L = \frac{\bar{v}}{f_2 - f_1}$$

$$\sigma_L = \sqrt{\left(\frac{\sigma_{\bar{v}}}{f_2 - f_1}\right)^2 + \left(\frac{\sigma_{f_1}}{(f_2 - f_1)^2}\right)^2 + \left(\frac{\sigma_{f_2}}{(f_2 - f_1)^2}\right)^2}$$

For the propagation velocity, the mean value $\bar{v}$ of the previously determined values is used:

$$\bar{v} = 3865 \pm 6 \text{ m/s}$$

The delay time τ can then be calculated as:

$$\tau = \frac{1}{f_2 - f_1}, \sigma_\tau = \sqrt{2} \frac{\sigma_{f_{1,2}}}{(f_2 - f_1)^2}$$

Example As an example, these values are calculated from the measured data of filter identifier "C31" (see Fig. 5), with the uncertainty of the measured frequencies chosen as $\sigma_{f_l} = \sigma_{f_r} = 0.001 \text{ MHz}$:

$$L = \frac{3865 \text{ m/s}}{102.840 \text{ MHz} - 101.477 \text{ MHz}} = 2836 \mu\text{m}$$

$$\sigma_L = \sqrt{\left(\frac{6 \text{ m/s}}{1.363 \text{ MHz}}\right)^2 + 2 \left(\frac{0.001 \text{ MHz}}{(1.363 \text{ MHz})^2}\right)^2} = 4 \mu\text{m}$$

Analogous to the above calculations, the values of L for all filters were determined and are listed in Table 4.

Discussion In Fig. 6, the values calculated from the measurements are plotted against the theoretically expected values. The theoretically expected slope of the graph is $a = 1$. A linear regression yields a slope of $a = 0.96$ and a y-axis intercept of $y = 224.24 \mu\text{m}$. From this, it can be concluded that the measurements of propagation velocity $\bar{v}$ and distance L were relatively accurate. The offset of approximately $220 \mu\text{m}$ that emerges from the measurement corresponds to an additional path length the signal must travel before it is registered. It is constant for all distances L and is very likely dependent on the measurement system.

5 INSERTION LOSS AND STOP BAND

Once the center frequency f_0 is known, the insertion loss can be read from the measured curve because it corresponds to the value of the transfer function at f_0 . The stop-band width corresponds to the difference between the measured power at the first maximum adjacent to f_0 and the insertion loss. For filter identifier "C31" ($d = 2535 \mu\text{m}$), the determination of these values is shown in Fig. 1. The theoretically expected stop-band value corresponds to the value of the transfer function $H(f)$ at the positions $f = f_0 \pm 3f_0/N$. The measured values of insertion loss and stop band for all filters are summarized in Table 5.

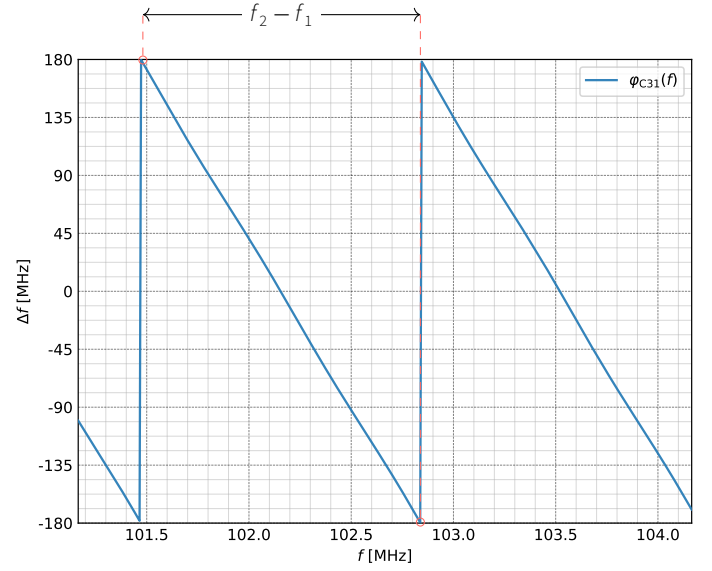


Figure 5 | Determination of $f_2 - f_1$ from the measured frequency-dependent phase (shown here for "C31").

Identifier	$a(2N - 1) + d$	$L[\mu\text{m}]$	$\bar{v}/(f_2 - f_1)$	$\tau[\mu\text{s}]$
"C31"	2718.3	2836(4)	2836(4)	733.7(8)
"C32"	2913.3	3036(5)	3036(5)	785.5(9)
"C33"	3108.3	3218(5)	3218(5)	833(1)
"C34"	3303.3	3352(5)	3352(5)	867(1)
"C35"	3498.3	3615(6)	3615(6)	936(1)
"B21"	3026.1	3251(5)	3251(5)	841(1)
"B22"	2988.5	3202(5)	3202(5)	829(1)
"B23"	2950.9	3124(5)	3124(5)	808.4(9)
"B24"	2913.3	3080(5)	3080(5)	796.8(9)
"B25"	2894.5	3036(5)	3036(5)	785.5(9)

Table 4 | Theoretically expected L and measured L and τ .

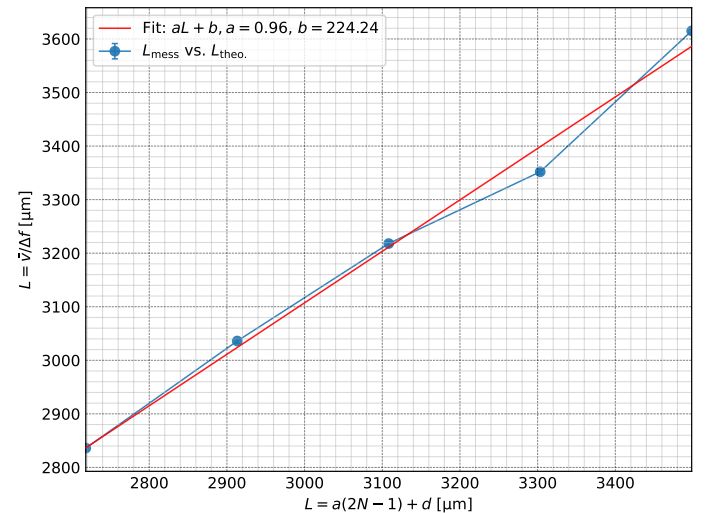


Figure 6 | Measured L plotted against the theoretically expected L .

6 SUMMARY OF RESULTS

The specifications of the filters obtained from the measurements are summarized in Table 6.

Identifier	Insertion Loss [dB]	Stop Band[dB]	
		from measured data	$H(f = f_0 \pm 3f_0/N)$
"C31"	12.7(5)	23.0(5)	26.8
"C32"	13.2(5)	23.5(5)	26.8
"C33"	16.6(5)	21.4(5)	26.8
"C34"	15.5(5)	24.0(5)	26.8
"C35"	12.4(5)	32.6(5)	26.8
"B21"	9.0(5)	21.3(5)	26.9
"B22"	9.4(5)	22.8(5)	26.8
"B23"	13.4(5)	22.7(5)	26.8
"B24"	12.3(5)	23.3(5)	26.7
"B25"	14.0(5)	24.2(5)	26.7

Table 5 | Insertion loss and stop band (theory and measurement).

REFERENCES

[1] A. Holm et al. "Investigation of surface acoustic waves on LiNbO3, quartz, and LiTaO3 by laser probing". In: *Microelectronic Engineering* 31.1 (1996). Electron and Optical Beam Testing of Electronic Devices, pp. 123–127. ISSN: 0167-9317. DOI: [https://doi.org/10.1016/0167-9317\(95\)00334-7](https://doi.org/10.1016/0167-9317(95)00334-7). URL: <https://www.sciencedirect.com/science/article/pii/0167931795003347>.

Identifier	f_0 [MHz]	Δf [MHz]	L [μm]	$\tau=1/(f_2-f_1)$ [μs]	Insertion loss[dB]	Stop Band[dB]
"C31"	102.7(4)	20.53(8)	2836(4)	733.7(8)	12.7(5)	23.0(5)
"C32"	102.6(4)	20.51(8)	3036(5)	785.5(9)	13.2(5)	23.5(5)
"C33"	102.5(4)	20.50(8)	3218(5)	833(1)	16.6(5)	21.4(5)
"C34"	102.5(4)	20.50(8)	3352(5)	867(1)	15.5(5)	24.0(5)
"C35"	103.2(4)	20.63(8)	3615(6)	936(1)	12.4(5)	32.6(5)
"B21"	89.6(4)	11.20(5)	3251(5)	841(1)	9.0(5)	21.3(5)
"B22"	89.5(4)	12.79(5)	3202(5)	829(1)	9.4(5)	22.8(5)
"B23"	89.5(4)	14.92(7)	3124(5)	808.4(9)	13.4(5)	22.7(5)
"B24"	89.7(4)	17.94(8)	3080(5)	796.8(9)	12.3(5)	23.3(5)
"B25"	89.6(4)	19.90(9)	3036(5)	785.5(9)	14.0(5)	24.2(5)
v = 3798(2) m/s						

Table 6 | Data sheet for all SAW filters. The value for velocity v was taken from the value obtained by linear regression.