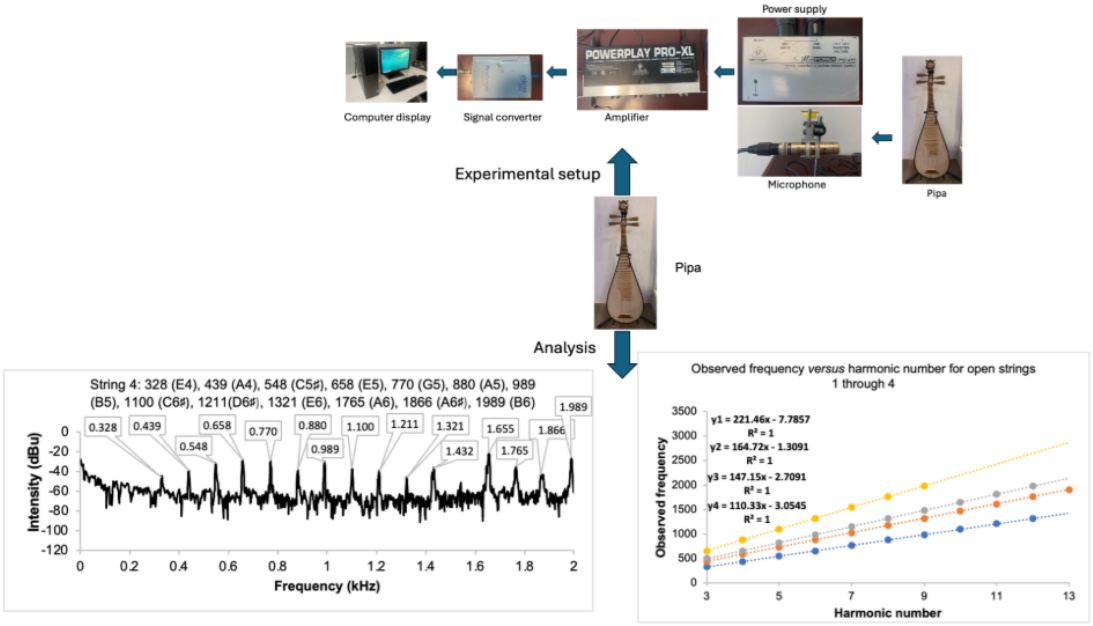
The Pipa: A Case Study of the Classic Chinese Lute – An Analysis of its Acoustic Characteristics

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GRAPHICAL ABSTRACT



The Pipa: A Case Study of the Classic Chinese Lute – An Analysis of its Acoustic Characteristics

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The Chinese pipa, a lute with a large number of frets, is known for its rich timbral and expressive capabilities. The sound signals were recorded in real time using a PC-based USB oscilloscope and associated data recorder. The digital storage oscilloscope program enabled voltage-based triggering and Fast Fourier Transform (FFT) analysis. While the heard notes according to the 12-Tone Equal Temperament (TET) tuning are A3, E3, D3, and A2, the digital oscilloscope recorded the harmonic frequency for open strings 1, 2, 3, and 4 as 880 Hz (A5=880.00), 656 Hz (E5=659.26), 586 Hz (D5=587.33), and 439 Hz (A4=440.00). Because of the occurrence where the listener claimed to recognize the note A2 while they heard A4, the measured frequencies do not match perceived notes. This is a well-known missing fundamental phenomenon. The pipa produces a complex overtone structure that is aligned with integer multiples of an implied fundamental over all strings and fret positions, according to the harmonic analysis. A3, A♯3/B♭3, B3, C4, C♯4, D4, D♯4, E4, F4, F♯4, G4, G♯4, A4, A♯4/B♭4, B4, C5, C♯5, D5, D♯5, E5, F5, F♯5, G5, G♯5, A5, A♯5/B♭5, B5, C6, C♯6, D6, E6 are the running notes for open string 1 and fret 1 through 30, which in semitone intervals consistent with modern equal temperament. Based on pure intervals, the pipa's 30 frets are widely separated and sonically pure.

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Keywords: Pipa; Fast Fourier transform (FFT); Harmonics; Missing fundamental

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INTRODUCTION

The pipa is a traditional Chinese plucked chordophone that has played an important role in Chinese classical and ensemble music for approximately two millennia. Its distinctive pear-shaped body, four strings, and extensive fretting system contribute to its characteristic tonal and expressive capabilities (Yeye 2023). The name pipa is derived from the terms *pi*, referring to forward plucking, and *pa*, referring to reverse plucking, terms documented during the Eastern Han Dynasty (25 to 220 CE) (Britannica Editors 2018). Although pipa historically referred to several types of plucked chordophones, the term has since become associated primarily with the modern pear-shaped instrument. Related instruments include the Japanese *biwa*, Korean *bipa*, and Vietnamese *đàn tỳ bà*. Modern pipas generally have four strings and approximately 29 to 31 frets, with nylon-wrapped steel strings replacing the silk strings historically used. The instrument is normally held

vertically and played with finger picks or artificial nails. Its expressive vocabulary includes tremolo, harmonics, vibrato, glissando, portamento, string bending, and various right-hand plucking techniques.

The pipa's acoustic characteristics are strongly influenced by the interaction between its structural materials, string tension, soundboard, and playing techniques. The body and neck are commonly constructed from dense hardwoods such as rosewood, red sandalwood, mahogany, or wenge, which provide structural stability under string tension and contribute to the instrument's tonal response. In contrast, the soundboard is generally made from seasoned paulownia, a relatively lightweight and acoustically responsive wood that facilitates vibration and sound radiation. This combination of a rigid hardwood frame and lighter soundboard is important to the pipa's characteristic bright, clear, and resonant tone. The age and seasoning of the wood may also affect its mechanical and acoustic properties, including responsiveness, sustain, and tonal stability. High-quality instruments may therefore use carefully seasoned timber to reduce dimensional changes and improve long-term stability.

The four strings are commonly tuned to A3–E3–D3–A2, although alternative tunings are used according to repertoire and regional performance traditions. The instrument's extensive fret system allows precise control of pitch as well as expressive effects such as string bending. Historically, pipa frets incorporated intervals approximating whole tones and semitones; the later expansion of the fret system toward semitonal divisions reflected the increasing influence of Western equal temperament (Lui *et al.* 2001). The fret material and geometry may also influence the mechanical coupling between the string and instrument body, while the large frets facilitate pitch bending and other expressive techniques.

The pipa's acoustic output is further shaped by its plucking techniques. The fundamental right-hand strokes, *tan* and *tiao*, produce different attack characteristics depending on the direction, position, and force of plucking. Left-hand techniques, including vibrato, portamento, harmonics, and string bending, modify pitch and spectral characteristics after the initial excitation of the string. Consequently, the pipa's timbre is not determined solely by its materials and construction, but also emerges from the interaction between string properties, body resonance, soundboard vibration, fret geometry, and performer-controlled excitation.

It is hypothesized that the pipa's distinctive construction, including its hardwood body, paulownia soundboard, four-string tuning, and closely spaced fret arrangement, contributes to a complex acoustic spectrum characterized by a strong fundamental frequency and multiple higher-order harmonics. The pipa's different playing techniques are also expected to produce measurable variations in harmonic content and spectral characteristics. These hypotheses will be evaluated through the acoustic measurements and analyses presented in this study.

Construction Materials and Their Relationship to Sound Quality

The acoustic characteristics of the pipa are closely related to its construction materials, geometry, and structural arrangement. The instrument generally consists of a rigid hardwood body and neck, together with a relatively lightweight and acoustically responsive soundboard, traditionally made from seasoned paulownia wood. Hardwoods such as rosewood, red sandalwood, mahogany, and wenge provide the structural stiffness required to withstand the tension of the four strings while also influencing the transmission

and reflection of vibrational energy within the instrument. Their density, stiffness, damping characteristics, and internal structure can affect the resonance, sustain, and tonal colour perceived by the listener. In contrast, paulownia is a relatively lightweight wood with favourable acoustic properties for a soundboard because it can respond efficiently to string excitation and radiate vibrational energy as sound. Thus, the contrast between the relatively rigid body and the more responsive soundboard is important for coupling string vibration to the surrounding air and contributes to the pipa's characteristically clear and resonant tone.

The structural configuration of the pipa also plays an important role in determining its acoustic response. The body, neck, pegbox, soundboard, bridge, strings, and fretting system form a coupled vibrating structure in which energy from the plucked string is transferred through the bridge and soundboard to the body. The stiffness and mass distribution of these components influence the natural modes of vibration and, consequently, the distribution of acoustic energy among the fundamental frequency and higher harmonics. The use of multiple frets, including the larger *xiang* frets and smaller *pin* (*ping*) frets, provides precise control of string length and therefore determines the fundamental frequencies available to the performer. The broad frets also permit string bending, which changes the effective tension of the string and produces characteristic pitch variations. In addition, the nylon-wound steel strings provide greater tensile strength and a different vibrational response from the historically used silk strings. Consequently, the pipa's distinctive timbre should be understood not as the result of a single material, but as the combined effect of string properties, wood density and stiffness, body geometry, soundboard responsiveness, bridge coupling, and fret arrangement. These construction features provide a physical basis for expecting measurable differences in resonance, harmonic structure, spectral distribution, and sound decay in acoustic analysis of the instrument.

To the best of the authors' knowledge, this study is the first to conduct a comprehensive acoustic analysis of the pipa, integrating its tuning system, frequency range, tonal characteristics, and the influence of its construction materials on its acoustic properties. In particular, the study provides a systematic characterization of the pipa's acoustic behavior based on experimental measurements and relates the observed acoustic features to the instrument's structural and performance characteristics. The findings contribute new acoustic data on this traditional Chinese instrument and provide a basis for understanding the relationship between pipa construction and sound production.

EXPERIMENTAL

In this study, a 30-fret traditional Chinese pipa was used. The dimensions are 102 to 105 cm in overall length, 31 to 32 cm in body width, and 5 to 14 cm in depth. It has a short neck and a pear-shaped, hollow wooden body. The tuning ranged from the highest to the lowest (string 1 to string 4) was as follows: A3 (220 Hz), E3 (164 Hz), D3 (146 Hz), and A2 (110 Hz). Figure 1 shows the pipa. To provide accurate and reliable sound production, a skilled musician plucked the pipa. Consistency was ensured by employing the same technique, plucking angle, and force on each attempt. The skilled musician rehearsed the precise motions multiple times prior to recording in order to minimize human error and enhance the precision of the sound comparison.

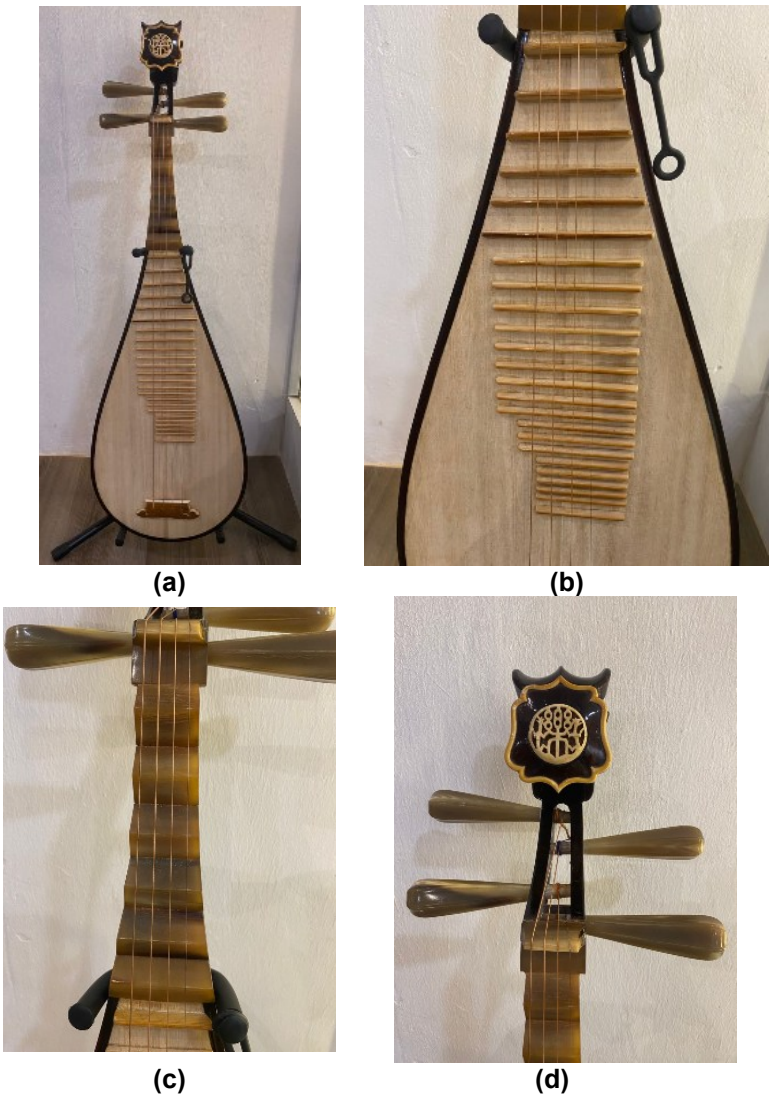


Fig. 1. (a) The Chinese pipa; (b) The bamboo frets; (c) The buffalo horn frets; (d) The buffalo horn pegs

The notes that were plucked were A3 (220 Hz), E3 (164 Hz), D3 (146 Hz), and A2 (110 Hz). They matched strings 1 through 4. To remove outside sound reflections, all recordings were made in an anechoic room. To record the radiated sound, an omnidirectional polar pattern microphone was placed 20 cm above the device. To simulate normal playing circumstances and provide the best possible sound resonance, both instruments were played in a traditional seated position. A PicoScope 3000 series oscilloscope and related data recorder (Pico Technology, Eaton Socon, UK) were used to record the sound signals in real time. Waveform viewing, voltage-based triggering, spectrum visualization, and Fast Fourier Transform (FFT) analysis were all made possible by the PicoScope program. The pipa was recorded in the same way, with a fixed microphone position and orientation, to avoid distortion or bias. Prior to being processed by the PicoScope, the signal was amplified using a Behringer Powerplay Pro XL amplifier (Zhongshan, Guangdong, China). Finding the fundamentals, harmonics, and subharmonics in the recorded waveforms was made possible by the Fourier transform technique. During

several experiments, sound data from the pipa were gathered. The same settings were used to record each iteration, and the waveforms that were produced were averaged to minimize noise and variability. This method guaranteed the instrument had a strong and significant acoustic. A clear, accurate, and scientifically valid assessment of the pipa's acoustic performance is ensured by the approach, which uses controlled plucking, standardized recording parameters, and numerous rounds of measurement with average data. Figure 2 shows a schematic diagram of the experimental setup.

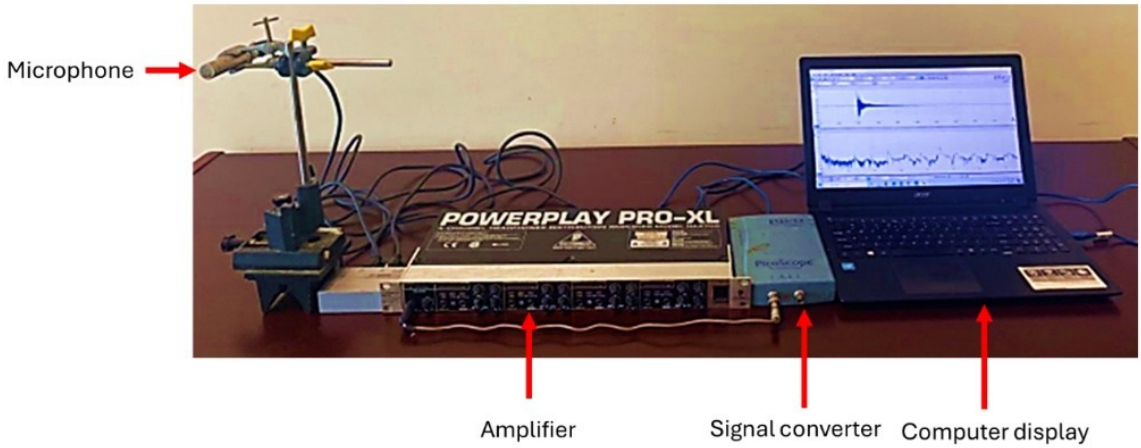


Fig. 2. Schematic diagram of the experimental setup

The acoustic signals were recorded in monophonic format with a sampling frequency of 48 kHz and a 24-bit resolution. Data acquisition and waveform visualization were performed using PicoScope software, which provided voltage-triggered recording, real-time waveform display, and spectral analysis. Prior to frequency analysis, each waveform was inspected to remove unwanted background noise and clipped sections. The FFT analysis was then applied using a Hann window with a window length of 4096 samples. When measuring a vibration signal with PicoScope, for the frequency span between 0 to 100,000 Hz and spectrum bins selected as 131,072 bins; Δf=100,000 Hz/131,072bins, approximately 0.763 Hz. The theoretical bin width is 0.763 Hz. For a standard Hann window, the effective resolution bandwidth becomes approximately 1.50 x 0.763 Hz = 1.144 Hz. This means that any two frequencies closer than approximately 1.144 Hz apart will blur together into a single peak. The fundamental frequency (f_0) was determined from the highest-amplitude spectral peak in the low-frequency region of the FFT spectrum. Subsequent prominent peaks were identified as partial frequencies to examine the harmonic characteristics of the instrument. The measured frequencies were then compared with the equal-tempered musical scale to determine the closest corresponding musical notes.

RESULTS AND DISCUSSION

Open-String Spectral Characteristics

This section explains the four tunings and identifies the dominant spectral peaks as harmonics. Strings 4, 3, 2 and 1 were tuned to A2 (110 Hz), D3 (146 Hz), E3 (164 Hz), A3

(220 Hz). Figures 3 show the FFT for string 4, 3, 2 and 1. String 4 (A2=110.00) shows the 328 (E4), 439 (A4), 548 (C5♯), 658 (E5), 770 (G5), 880 (A5), 989 (B5), 1100 (C6♯), 1211 (D6♯), 1321 (E6), 1765 (A6), 1866 (A6♯), 1989 (B6) peaks. String 3 (D3=146.83) shows the 438 (A4), 586 (D5), 735 (F5♯), 880 (A5), 1027 (C6), 1173 (D6), 1322 (E6), 1469 (F6♯), 1615 (G6♯), 1763 (A6), 1911 (A5♯) peaks. String 2 (E3=164.81) shows the 494 (B4), 656 (E5), 823 (G5♯), 987 (B5), 1151 (D6), 1317 (E6), 1481 (F6♯), 1646 (G6♯), 1810 (A6), 1976 (B6) peaks. String 1 (A3=220.00) shows the 655 (E5), 880 (A5), 1100 (D6), 1320 (E6), 1544 (G6), 1762 (A6), 1986 (B6) peaks.

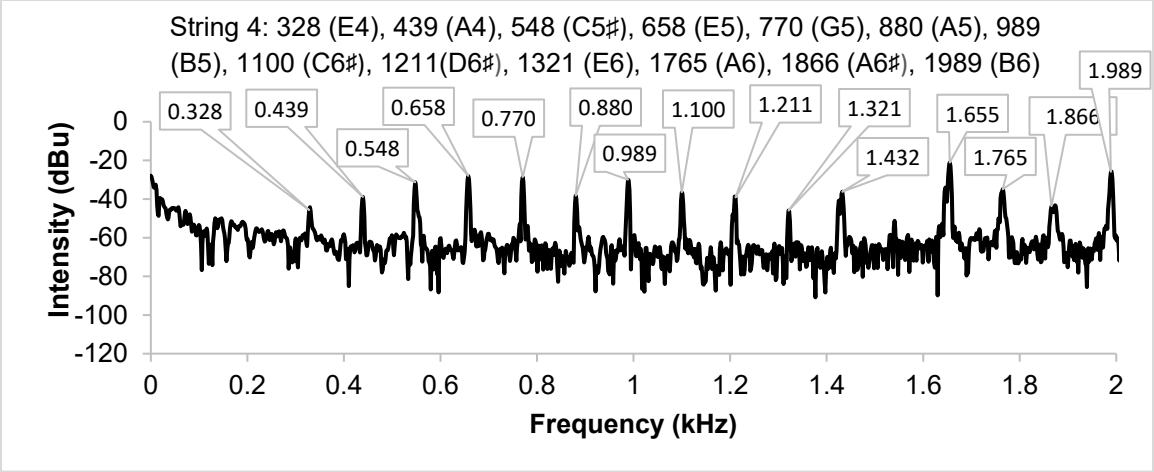


Fig. 3a. String 4 (A2=110): 328 (E4), 439 (A4), 548 (C5♯), 658 (E5), 770 (G5), 880 (A5), 989 (B5), 1100 (C6♯), 1211 (D6♯), 1321 (E6), 1765 (A6), 1866 (A6♯), 1989 (B6)

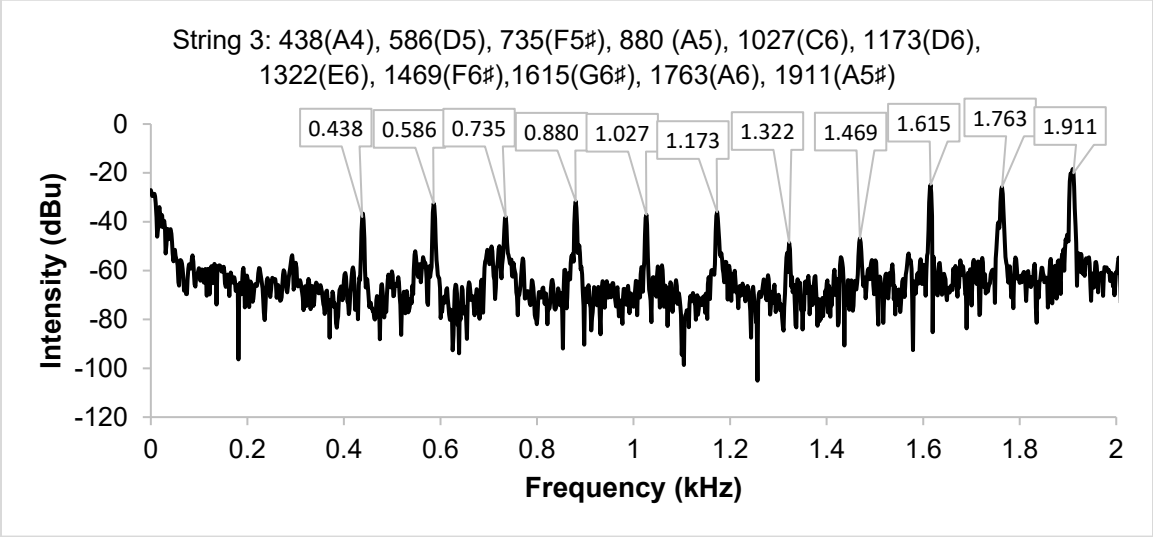


Fig. 3b. String 3 (D3=146): 438 (A4), 586 (D5), 735 (F5♯), 880 (A5), 1027 (C6), 1173 (D6), 1322 (E6), 1469 (F6♯), 1615 (G6♯), 1763 (A6), 1911 (A5♯)

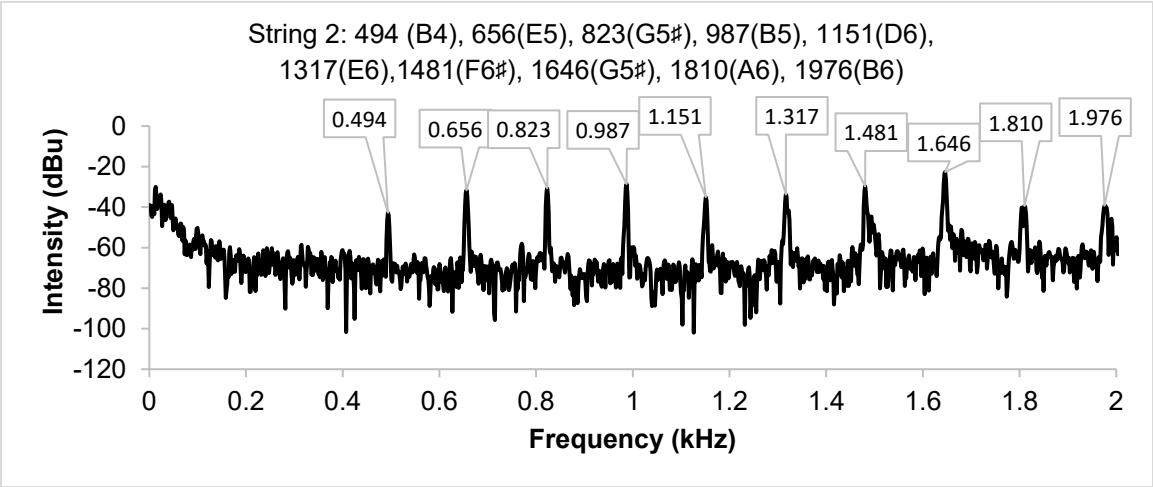


Fig. 3c. String 2 (E3=164.81): 494 (B4), 656 (E5), 823 (G5♯), 987 (B5), 1151 (D6), 1317 (E6), 1481 (F6♯), 1646 (G5♯), 1810 (A6), 1976 (B6)

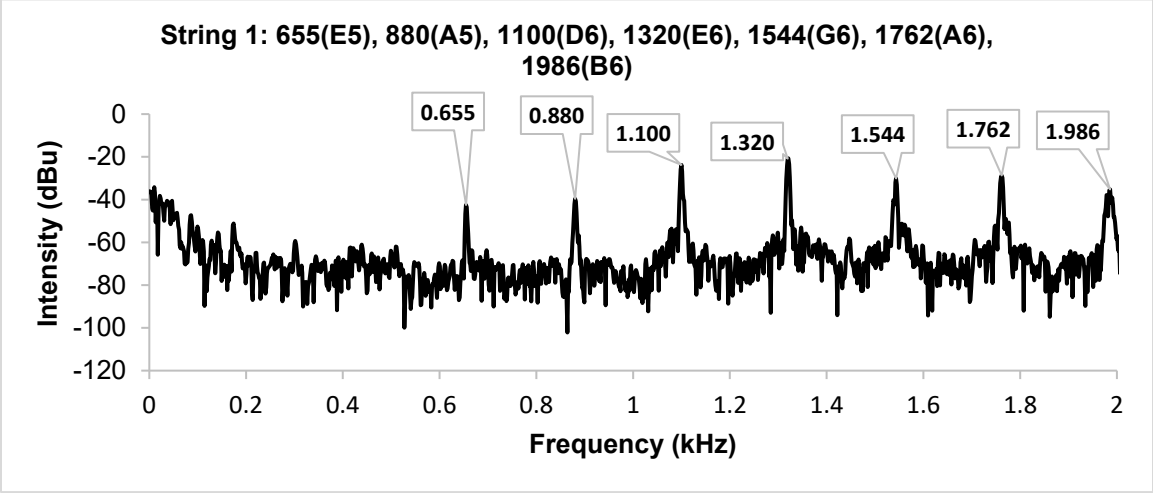


Fig. 3d. String 1 (A3=220.00): 655 (E5), 880 (A5), 1100 (D6), 1320 (E6), 1544 (G6), 1762 (A6), 1986 (B6)

Estimation of the Missing Fundamental

This section explains that the measured peaks correspond to nf_0 and use linear regression of frequency against harmonic number to estimate f_0**.** When a string is tuned to A2 = 110 Hz, the frequency spectrum will display numerous overtones (harmonics) in addition to 110 Hz. E4, A4, C♯5, and so on are all components of the 110 Hz harmonic series. The fundamental frequency, or the lowest frequency generated when the entire string vibrates, is the fundamental A2 = 110 Hz. Naturally, a vibrating string will vibrate in integer multiples of its fundamental ($f_n = n \times 110$ Hz). They are nearly precise multiples of 110 Hz. Real strings never vibrate in a single mode. The entire string vibrates at 110 Hz when plucked, followed by the halves at 220 Hz, the thirds at 330 Hz, the fourths at 440 Hz, and so on. These all take place at the same time. The missing fundamental phenomenon is when the ear can detect 110 Hz well even when the fundamental is physically weak. The missing fundamental is a psychoacoustic phenomenon; this is due to the measured

spectrum containing higher harmonics while the expected fundamental is absent or substantially weaker than higher partials. Nevertheless, the harmonic spacing corresponds to f_0 and the auditory system can perceive the pitch corresponding to f_0 from the harmonic relationship. Tables 1a–1d show the harmonic number n, ideal frequency nf_0, approximate note and the observed frequency for strings 4 through 1. Figure 4 shows the observed frequency *versus* harmonic number for strings 1 through 4.

Table 1a-1d. The Harmonic Number n, ideal frequency n_{f0}, approximate note and the observed frequency for strings 4 through 1

Table 1a

Harmonic number n	Ideal frequency n_{f0}	Approx. note	Observed String 4
3	330.00	E4	328
4	440.00	A4	439
5	550.00	C♯5	548
6	660.00	E5	658
7	770.00	G5	770
8	880.00	A5	880
9	990.00	B5	989
10	1100.00	C♯6	1100
11	1210.00	D♯6	1211
12	1320.00	E6	1321

Table 1b

Harmonic Number n	Ideal Frequency n_{f0}	Approx. Note	Observed String 3
3	440.49	A4	438
4	587.32	D5	586
5	734.15	F5♯	735
6	880.98	A5	880
7	1027.81	C6	1027
8	1174.64	D6	1173
9	1321.47	E6	1322
10	1468.30	F6♯	1469
11	1615.13	G6♯	1615
12	1761.96	A6	1763
13	1908.79	A5♯	1911

Table 1c

Harmonic Number n	Ideal Frequency n_{f0}	Approx. Note	Observed String 2
3	494.43	B4	494
4	659.24	E5	656
5	824.05	G5♯	823
6	988.86	B5	987
7	1153.67	D6	1151
8	1318.48	E6	1317
9	1483.29	F6♯	1481
10	1648.10	G6♯	1646
11	1812.91	A6	1810
12	1977.72	B6	1976

Table 1d

Harmonic Number *n*	Ideal Frequency n_{f0}	Approx. Note	Observed String 1
3	660	E5	655
4	880	A5	880
5	1100	D6	1100
6	1320	E6	1320
7	1540	G6	1544
8	1760	A6	1762
9	1980	B6	1986

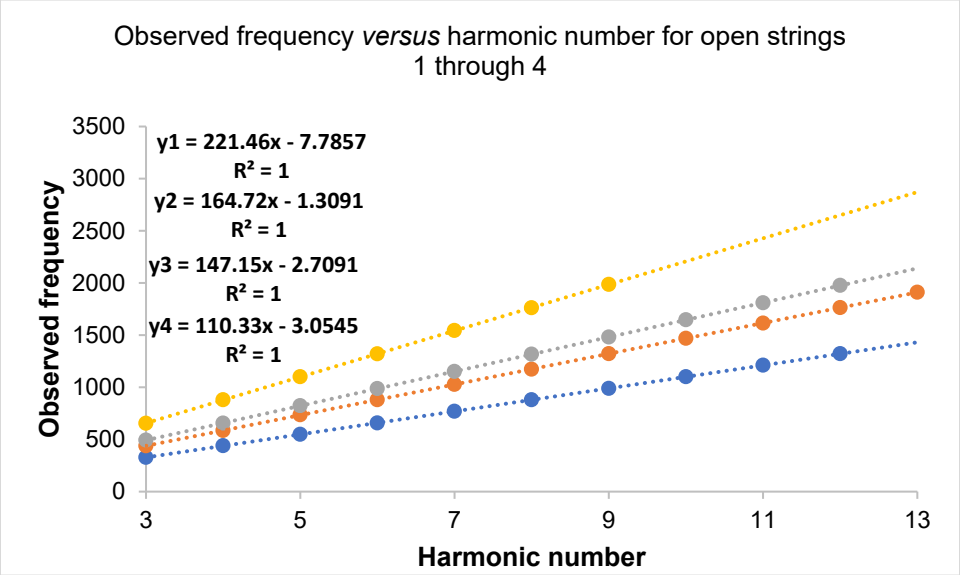


Fig. 4. Observed frequency *versus* harmonic number for open strings 1 through 4

Although string 4 displayed frequencies at 439 Hz (A4), 880 Hz (A5), and 1765 Hz (A6) instead of 110 Hz (A2) the gradient obtained from the partial frequency *versus* partial number was 110.33 Hz. String 3 displayed frequencies 586 Hz (D5), and 1173 Hz (D6) instead of 146 Hz (D3), the gradient obtained was 147.15 Hz. String 2 displayed 656 Hz (E5), 1317 Hz (E6) instead of 164.81 Hz (E3), the gradient obtained was 164.72 Hz. String 1 displayed 880 Hz (A5), 1762 Hz (A6) instead of 220.00 Hz (A3), the gradient obtained was 221.46 Hz. When a listener claims to recognize the note A2 when they hear A4, it is known as the missing fundamental phenomenon. The missing fundamental phenomenon is the sense of pitch when the waveform's first harmonic is absent (Howard and Angus 2017). Psychoacoustics has demonstrated that if there is a significant set of harmonics in the spectrum, the auditory system's innate ability to discriminate between tones leads it to consistently assign a pitch to a complex tone (Hartman 1996). A note with a pitch of 100 Hz, for instance, will have frequency components that are integer multiples of that value, such as 100, 200, 300, 400, and 500 Hz. This note's tone is not pure. However, the 100 Hz component in this case might be absent since smaller loudspeakers might not be able to create low frequencies. There might still be a fundamental-corresponding note audible.

Fret Frequencies and Chromatic Sequence

This section presents the 30-fret regressions and the corrected note names from 12-TET. The notes for open string 1 and fret 1 through 30 are A3, A♯3/B♭3, B3, C4, C♯4, D4, D♯4, E4, F4, F♯4, G4, G♯4, A4, A♯4/B♭4, B4, C5, C♯5, D5, D♯5, E5, F5, F♯5, G5, G♯5, A5, A♯5/B♭5, B5, C6, C♯6, D6, E6 as shown by the FFT spectra in the appendix. Figures 5a, 5b, and 5c display the observed frequency *versus* partial number for frets 1 through 10, frets 11 through 20, and frets 21 through 30, respectively. Table 2 displays the notes and the intervals between the frets obtained from the FFT spectra in the Appendix.

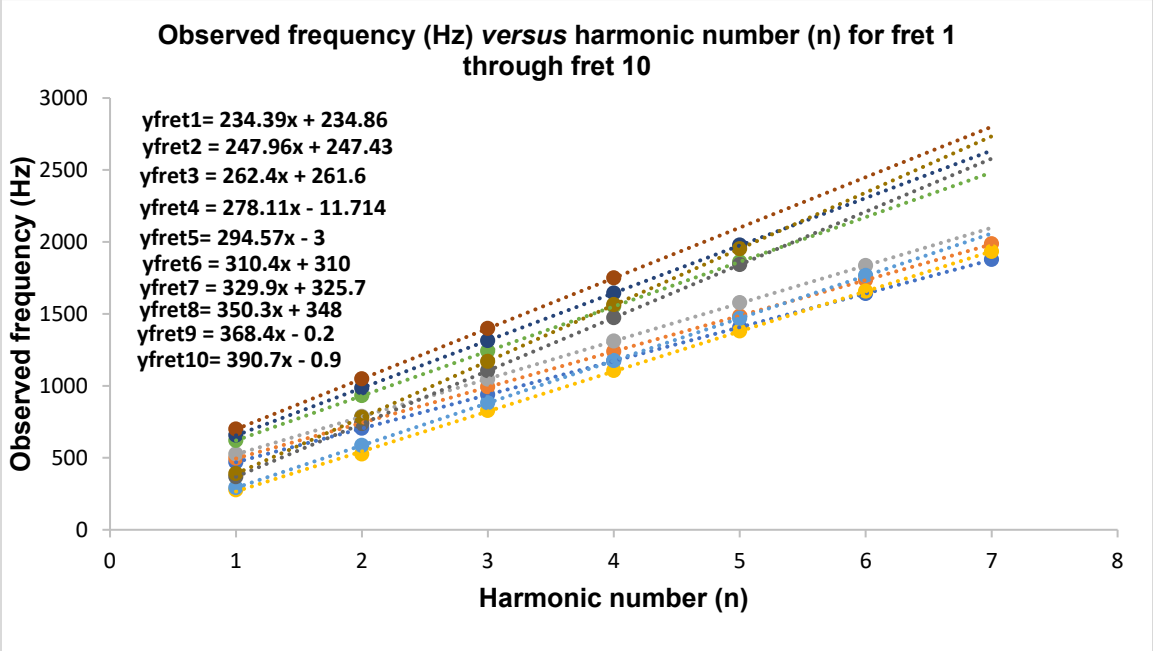


Fig. 5a. Observed frequency *versus* harmonic number for frets 1 through 10

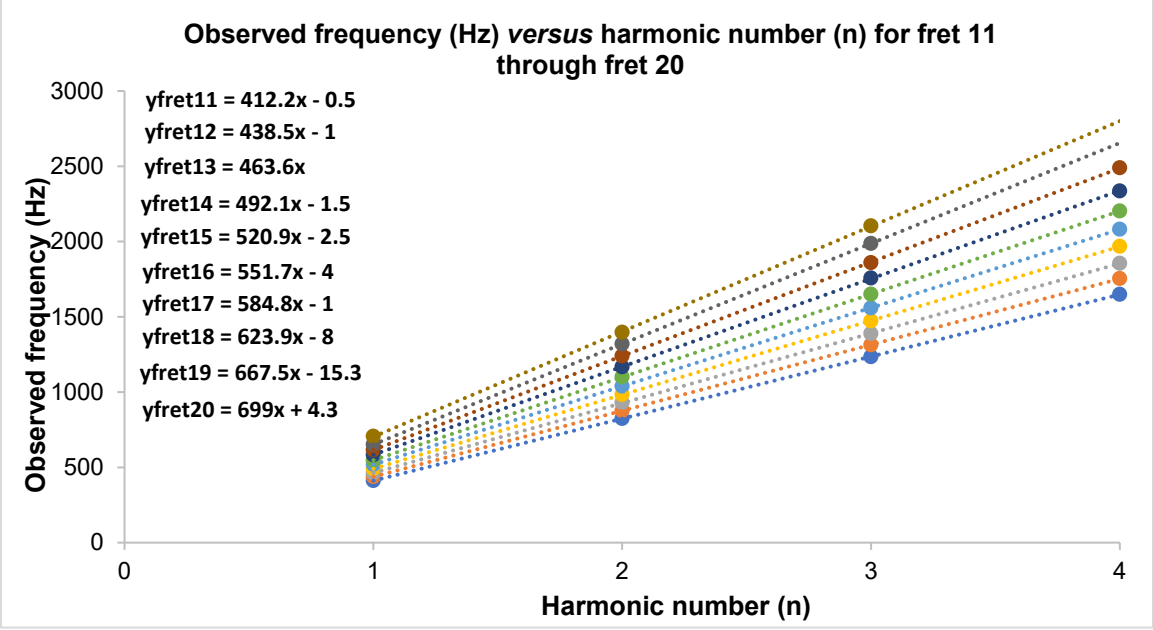


Fig. 5b. Observed frequency *versus* harmonic number for frets 11 through 20

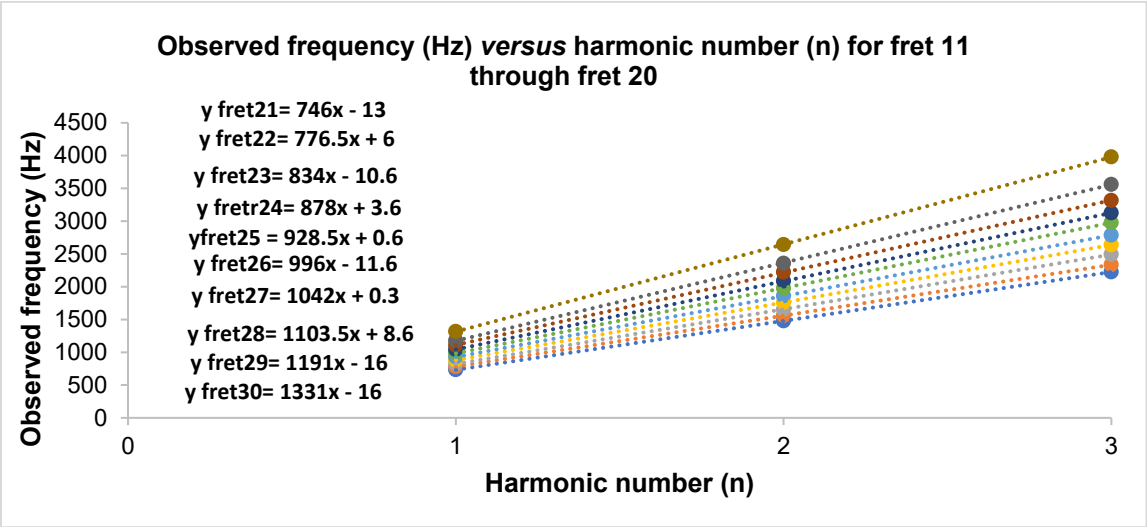


Fig. 5c. Observed frequency *versus* harmonic number for frets 21 through 30

From Figs. 5a, 5b, and 5c, the following Eqs. 1 to 30 are obtained:

y fret1 = 234.39x + 234.86, m = 234.39 (A3♯) (1)
y fret2 = 247.96x + 247.43, m = 247.96 (B3) (2)
y fret3 = 262.4x + 261.6, m = 262.40 (C4) (3)
y fret4 = 278.11x - 11.714, m = 278.11 (C4♯) (4)
y fret5 = 294.57x - 3, m = 294.57 (D4) (5)
y fret6 = 310.4x + 310, m = 310.40 (D4♯) (6)
y fret7 = 329.9x + 325.7, m = 329.90 (E4) (7)
y fret8 = 350.3x + 348, m = 350.30 (F4) (8)
y fret9 = 368.4x - 0.2, m = 368.40 (F4♯) (9)
y fret10 = 390.7x - 0.9, m = 390.70 (G4) (10)
y fret11 = 412.2x - 0.5, m = 412.2 (G4♯) (11)
y fret12 = 438.5x - 1, m = 438.5 (A4) (12)
y fret13 = 463.6x, m = 463.6 (A4♯) (13)
y fret14 = 492.1x - 1.5, m = 492.1 (B4) (14)
y fret15 = 520.9x - 2.5, m = 520.9 (C5) (15)
y fret16 = 551.7x - 4, m = 551.7 (C5♯) (16)
y fret17 = 584.8x - 1, m = 584.8 (D5) (17)
y fret18 = 623.9x - 8, m = 623.9 (D5♯) (18)
y fret19 = 667.5x - 15.33, m = 667.5 (E5) (19)
y fret20 = 699x + 4.33, m = 699 (F5) (20)
y fret21 = 746x - 13, m = 746 (F5♯) (21)
y fret22 = 776.5x + 6, m = 776 (G5) (22)
y fret23 = 834x - 10.667, m = 834 (G5♯) (23)
y fretr24= 878x + 3.6667, m = 878 (A5) (24)
y fret25 = 928.5x + 0.6667, m = 928 (A5♯) (25)
y fret26 = 996x - 11.667, m = 996 (B5) (26)
y fret27 = 1042x + 0.3333, m = 1042 (C6) (27)
y fret28 = 1103.5x + 8.6667, m = 1103 (C6♯) (28)
y fret29 = 1191x – 16, m =1191 (D6) (29)
y fret30 = 1331x – 16, m = 1331 (E6) (30)

Table 2. The Notes from FFT Spectra Obtained from the Appendix and the Intervals between the Frets

Fret Number	Lowest Note	Interval between Fret	*m*
Open String 1	A3	-	221.46 (A3)
1	A3♯	A4♯-A4=S	234.39 (A3♯)
2	B3	A4♯-B4=S	247.96 (B3)
3	C4	B4-C5=S	262.40 (C4)
4	C4♯	C5-C5♯=S	278.11 (C4♯)
5	D4	C5♯-D5=S	294.57 (D4)
6	D4♯	D5-D5♯=S	310.40 (D4♯)
7	E4	D5♯-E5=S	329.90 (E4)
8	F4	E5-F5=S	350.30 (F4)
9	F4♯	F5-F5♯=S	368.40 (F4♯)
10	G4	F5♯-G5=S	390.70 (G4)
11	G4♯	G5-G5♯=S	412.2 (G4♯)
12	A4	G5♯-A5=S	438.5 (A4)
13	A4♯	A5-A5♯=S	463.6 (A4♯)
14	B4	A5♯-B5=S	492.1 (B4)
15	C5	B5-C6=S	520.9 (C5)
16	C5♯	C6-C6♯=S	551.7 (C5♯)
17	D5	C6♯-D6=S	584.8 (D5)
18	D5♯	D6-D6♯=S	623.9 (D5♯)
19	E5	D6♯-E6=S	667.5 (E5)
20	F5	E6-F6=S	699 (F5)
21	F5♯	F6-F6♯=S	746 (F5♯)
22	G5	F6♯-G6=S	776 (G5)
23	G5♯	G6-G6♯=S	834 (G5♯)
24	A5	G6♯-A6=S	878 (A5)
25	A5♯	A6-A6♯=S	928 (A5♯)
26	B5	A6♯-B6=S	996 (B5)
27	C6	B6-C7=S	1042 (C6)
28	C6♯	C7-C7♯=S	1103 (C6♯)
29	D6	C7♯-D7=S	1191 (D6)
30	E6	D7-E7=T	1331 (E6)

Note: "*m*" is obtained from the gradient of the observed frequency *versus* harmonic number from Figs. 5a, 5b, and 5c.

The yfret 30 = 1331x − 16**,** *m* = 1331 (E6). If the open string is A3 = 220 Hz and the 30th fret is supposed to be E6, the expected equal-temperament frequency is approximately 1318.5 Hz, so 1331 Hz is about 0.8 to 1.0% higher. Similarly, several measured values differ noticeably from ideal 12-TET values. The measured fret frequencies generally follow the expected chromatic sequence, although deviations from ideal 12-TET frequencies occur, particularly at higher registers. Starting at the open string 1, the frets of the 30-fret pipa were set in intervals that were similar to the Western tone and semitone: semitone (S) intervals across the first 29 frets, concluding with a whole-tone (T) interval at the 30th fret T. From Table 2, the spectra display the lowest notes which are one octave higher than the gradient m of the observed frequency *versus* harmonic number. Although all the spectra display the missing fundamental, the gradient *m* displays the real fundamental frequency of each fret.

Relationship between Material Characteristics and Acoustic Response

The acoustic characteristics observed in the present study can be related to the material composition and structural construction of the pipa described in the introduction. In particular, the combination of a relatively stiff hardwood body and a lightweight paulownia soundboard provides an important structural basis for the observed resonance and harmonic response. The four strings introduce vibrational energy into the bridge and soundboard, while the wooden body acts as a supporting structure and acoustic cavity. Consequently, the measured spectrum represents not only the vibration of the strings but also the coupled response of the strings, soundboard, body, and enclosed air.

The predominance of higher-frequency partials in the measured spectra indicates that the pipa has a pronounced overtone response rather than producing a spectrum dominated exclusively by the fundamental frequency. This behavior is consistent with the construction of the instrument using a relatively stiff hardwood frame together with a lightweight and acoustically responsive Paulownia soundboard. The hardwood body provides structural rigidity against the tension of the four strings, while the lower-density soundboard can respond efficiently to the vibrational excitation transmitted through the bridge. This combination can facilitate the radiation of higher-frequency components and therefore contributes to the characteristically clear, focused, and bright timbre of the pipa. The results should therefore be interpreted as the acoustic consequence of a coupled wood-string system rather than as the response of an isolated ideal string.

The material properties of the soundboard are particularly important because the soundboard is the principal radiating surface of the instrument. Paulownia is a relatively lightweight wood and is traditionally selected for soundboards because its low mass and appropriate stiffness permit efficient vibration. When the string energy is transferred through the bridge, the soundboard can undergo bending vibration and convert part of the mechanical vibration into airborne sound. The measured presence of numerous higher partials across all four strings suggests that this structural coupling contributes to the broad frequency content observed in the FFT spectra. At the same time, the hardwood body and neck provide the stiffness required to maintain the geometry of the instrument under string tension and to support the soundboard without excessive structural deformation.

The differences between the measured partial frequencies and the ideal integer harmonic series also indicate that the pipa should not be considered a perfectly ideal string system. In a real instrument, the vibrating strings are coupled to the bridge, soundboard, body, and air cavity. The mechanical impedance of these components can alter the amplitude and, to a smaller extent, the frequency of individual partials. String stiffness, termination conditions at the bridge and frets, and energy transfer between the string and wooden structure may consequently produce deviations from the ideal harmonic model. Therefore, the measured harmonic structure can be regarded as a combined response of the string and the material-structural system of the pipa.

The fret system also contributes to the measured acoustic behavior. In the investigated instrument, the main frets are made of bamboo, while buffalo horn components are used in selected structural elements. These materials provide hard contact surfaces for the strings and help maintain consistent string termination during fretting. The stiffness and hardness of the fret material influence the mechanical boundary condition at the point where the vibrating string is contacted. A relatively rigid termination can reduce energy loss at the contact point and help preserve the higher-frequency components generated during plucking. Thus, the material selection of the frets, although secondary to

the soundboard and body, can contribute to the consistency and clarity of the measured spectral response.

The monoxyle-type construction described in the introduction, in which the body, neck, and pegbox can be formed from a continuous hardwood structure, is also relevant to the acoustic results. A continuous and mechanically stable structure provides a consistent path for transmission of vibrational energy from the string and bridge into the body. This structural continuity may reduce unwanted mechanical losses and assist in maintaining the characteristic focused response of the instrument. Differences in hardwood species, density, stiffness, damping, moisture content, and aging, however, are expected to modify the magnitude of individual spectral components. Consequently, the present FFT results should not be interpreted as representing a universal acoustic signature for all pipas, but rather as the response of the particular material combination and construction examined in this study.

The observed missing-fundamental behavior further demonstrates the interaction between material response and human auditory perception. Although the lowest fundamental components of some open strings were weak or absent in the measured radiated spectrum, the harmonic series retained sufficient periodic information for the fundamental pitch to be inferred. The material system of the pipa therefore influences the spectral energy distribution, while the auditory system integrates the available harmonic information to determine the perceived pitch. This provides an important connection between the physical properties of the instrument and the psychoacoustic characteristics discussed in this study.

Overall, the findings demonstrate that the acoustic performance of the pipa is closely associated with its material and structural design. The hardwood body provides mechanical strength and resistance to string-induced deformation, while the lightweight paulownia soundboard facilitates vibrational response and acoustic radiation. The bamboo and buffalo horn components provide rigid contact and support surfaces, and the overall structural arrangement determines how vibrational energy is distributed between the strings, body, soundboard, and air. The harmonic-rich spectra and the consistent frequency gradients obtained from the FFT analysis can therefore be understood as manifestations of this coupled material-acoustic system. This relationship between wood selection, structural stiffness, vibration transmission, and radiated sound reinforces the relevance of traditional pipa construction to a material-science perspective and provides a basis for future studies correlating specific wood properties, such as density, elastic modulus, damping coefficient, and moisture content, with measurable acoustic parameters.

CONCLUSIONS

1. The acoustic behavior of the pipa is influenced by its harmonic structure and psychoacoustic perception. The findings show that higher harmonics, rather than the fundamental frequency, dominate the pipa's radiated sound, revealing the instrument's natural overtone-rich timbre.
2. The PicoScope spectra of open strings 1–4 (highest to lowest) was dominated by higher harmonic partials, with prominent peaks near 880, 656, 586, and 439 Hz, respectively. These frequencies correspond approximately to higher harmonics of the tuned

fundamentals A3, E3, D3, and A2 rather than to the fundamental frequencies themselves. Linear regression of partial frequency against harmonic number yielded fundamental-frequency estimates of approximately 221.46, 164.72, 147.15, and 110.03 Hz for strings 1-4, respectively.

3. The running notes for open string 1 (continuous chromatic range) and frets 1 to 30 are as follows: A3, A♯3/B♭3, B3, C4, C♯4, D4, D♯4, E4, F4, F♯4, G4, G♯4, A4, A♯4/B♭4, B4, C5, C♯5, D5, D♯5, E5, F5, F♯5, G5, G♯5, A5, A♯5/B♭5, B5, C6, C♯6, D6, E6. Even though the estimated fundamental frequencies are absent from the spectral data, the fundamental is inferred from the harmonic series rather than directly observed.
4. The measured fret frequencies generally follow the expected chromatic sequence, although deviations from ideal 12- Tone Equal Temperament (TET) frequencies occur, particularly at higher registers. Even though the fret system mostly follows semitone intervals of equal temperament, minor differences in frequency gradients point to the preservation of conventional tuning aesthetics.
5. The acoustic response of the pipa is closely associated with its material and structural configuration. The hardwood body provides structural stiffness and supports the string tension, while the lightweight paulownia soundboard facilitates vibrational response and acoustic radiation. The bamboo and buffalo horn components provide relatively rigid string-contact and structural surfaces. The observed harmonic-rich spectra therefore arise from the coupled response of the strings, bridge, soundboard, wooden body, and enclosed air rather than from an ideal string alone. Variations in wood density, stiffness, damping, moisture content, and aging are expected to influence the amplitude and distribution of the radiated partials.
6. The observed spectral characteristics can be interpreted in the context of the pipa's construction, in which the strings, soundboard, body cavity, and fret structure jointly determine vibration transmission and sound radiation. Because the present study did not separately measure the mechanical and acoustic properties of the individual construction materials, their specific contributions cannot be quantitatively separated.
7. The pipa is an excellent illustration of how traditional instrument design combines perceptual phenomena with acoustical efficiency to produce a sound that is both perceptually integrated and physically challenging.

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APPENDIX

Figure A1 shows the FFT for fret 1 to 30 from string 1.

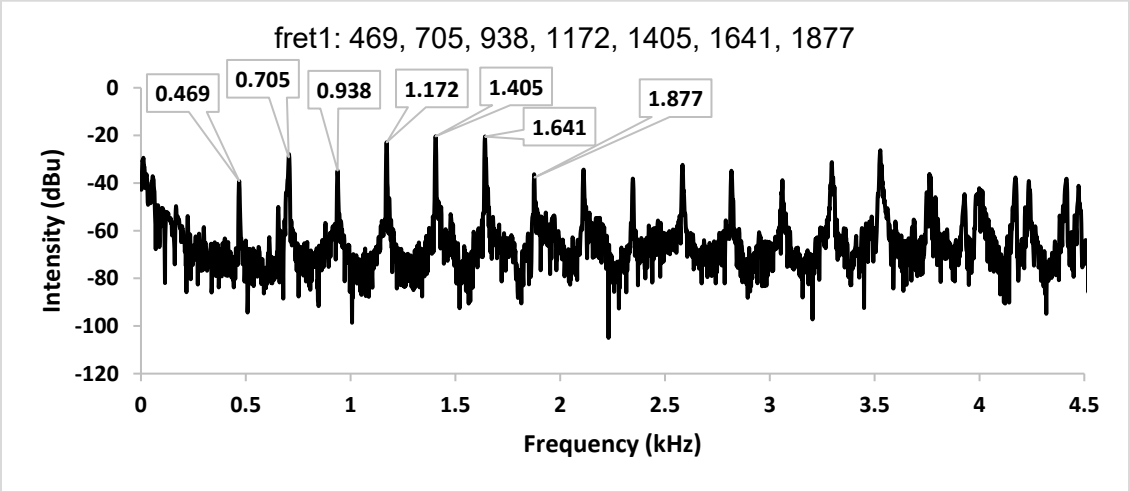


Fig. A1a. Fret 1. 469 (A4♯), 705 (F5), 938 (A5♯), 1172 (D6), 1405 (F6), 1641 (G6♯), 1877 (A6♯)

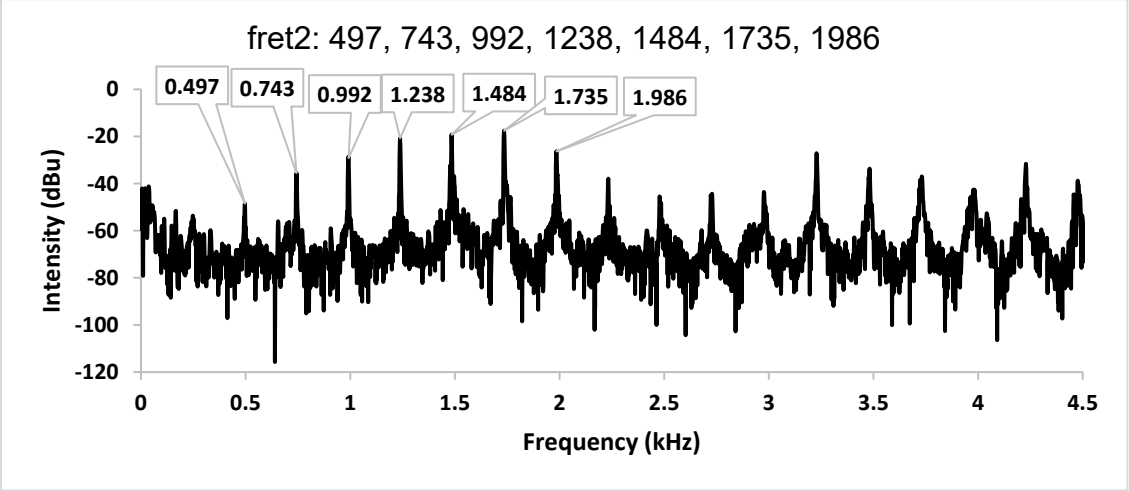


Fig. A1b. Fret 2: 497 (B4), 743 (F5♯), 992 (B5), 1238 (D6♯), 1484 (F6♯), 1735 (A6), 1986 (B6)

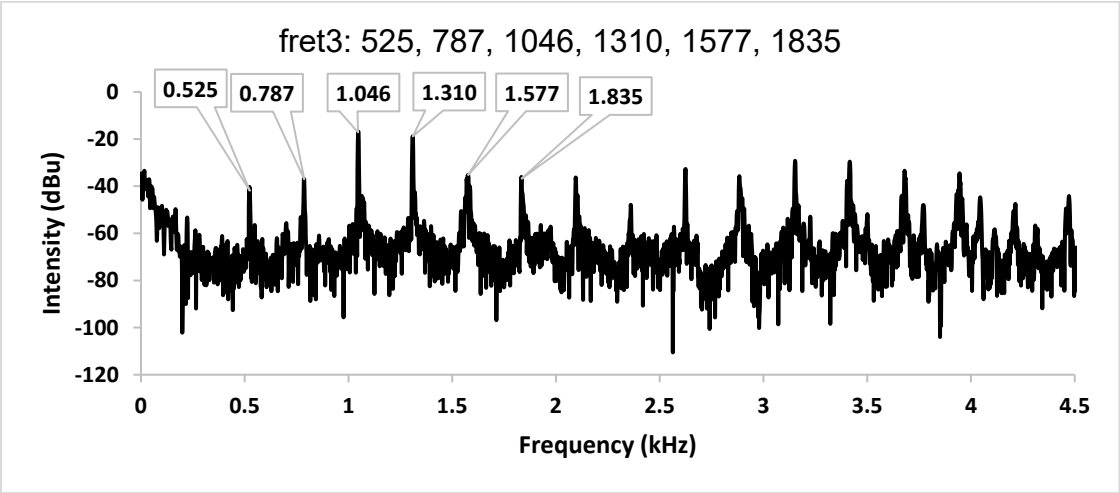


Fig. A1c. Fret 3: 525 (C5), 787 (G5), 1046 (C6), 1310 (E6), 1577 (G6), 1835 (A6♯)

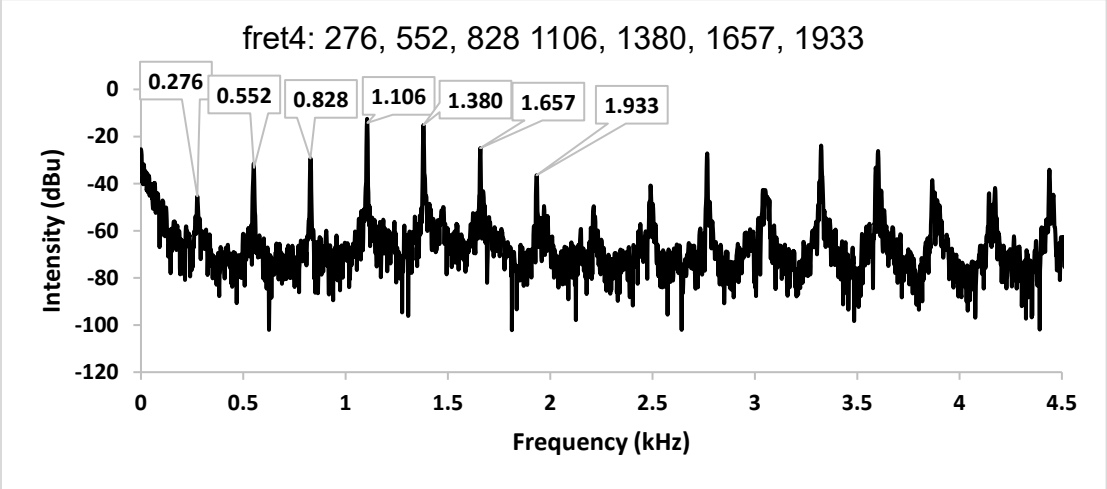


Fig. A1d, Fret 4: 276 (C4♯), 552 (C5♯), 828 (G5♯), 1106 (C6♯), 1380 (F6), 1657 (G6♯), 1933 (B6)

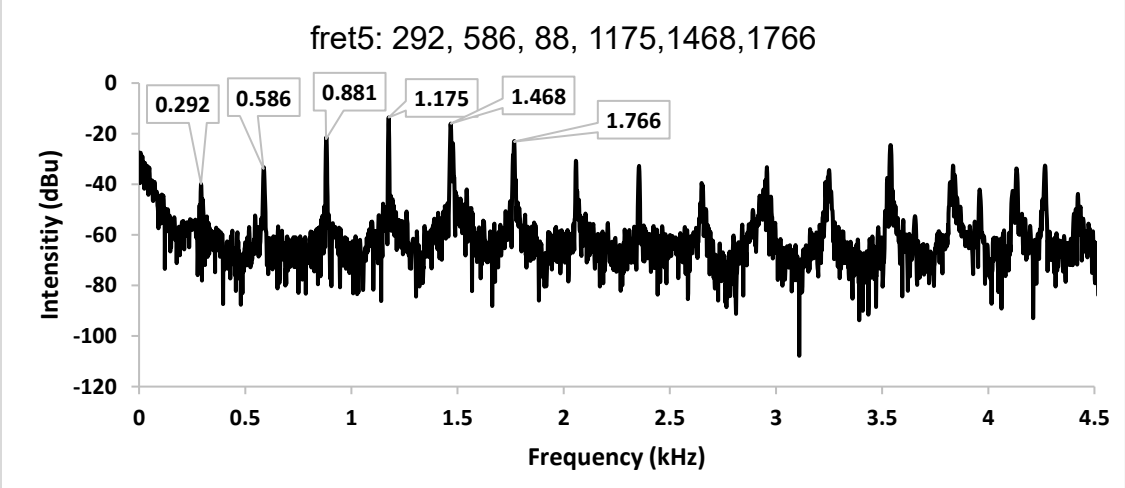


Fig. A1e. Fret 5: 292 (D4), 586 (D5),881 (A5), 1175 (D6), 1468 (F6♯), 1766 (A6)

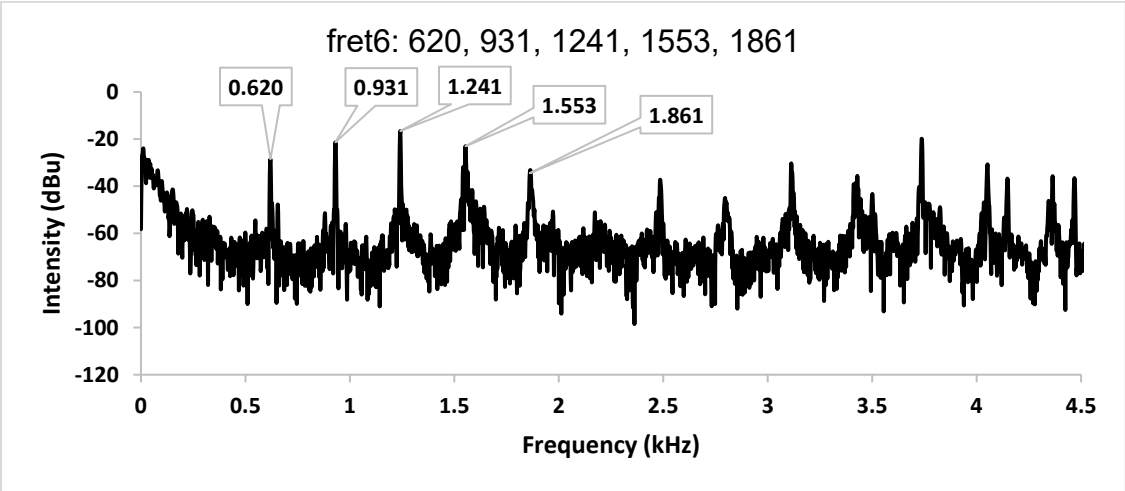


Fig. A1f. Fret 6: 620 (D5♯), 931 (A5♯), 1241 (D6♯), 1553 (G6), 1861 (A6♯)

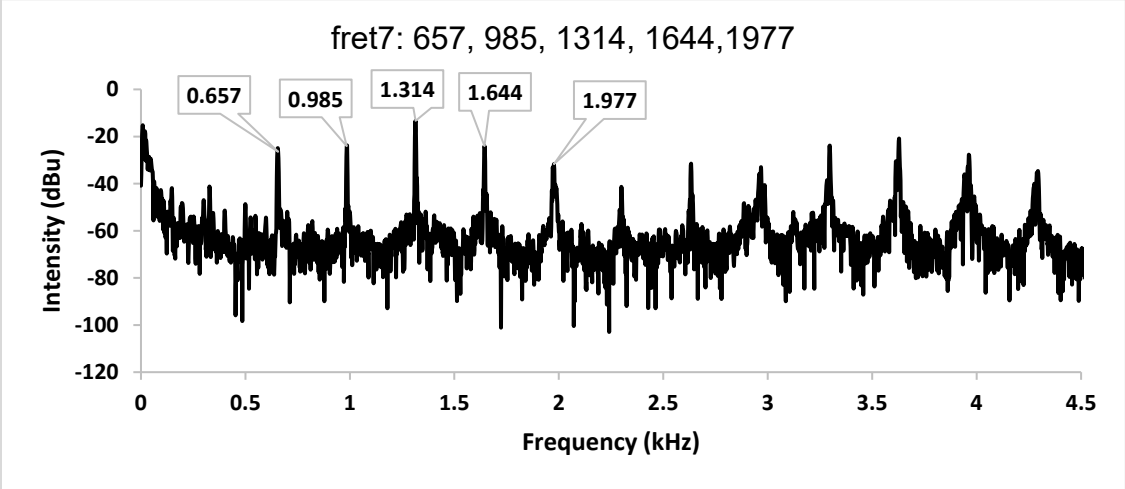


Fig. A1g. Fret 7: 657 (E5), 985 (B5), 1314 (E6), 1644 (G6♯), 1977 (B6)

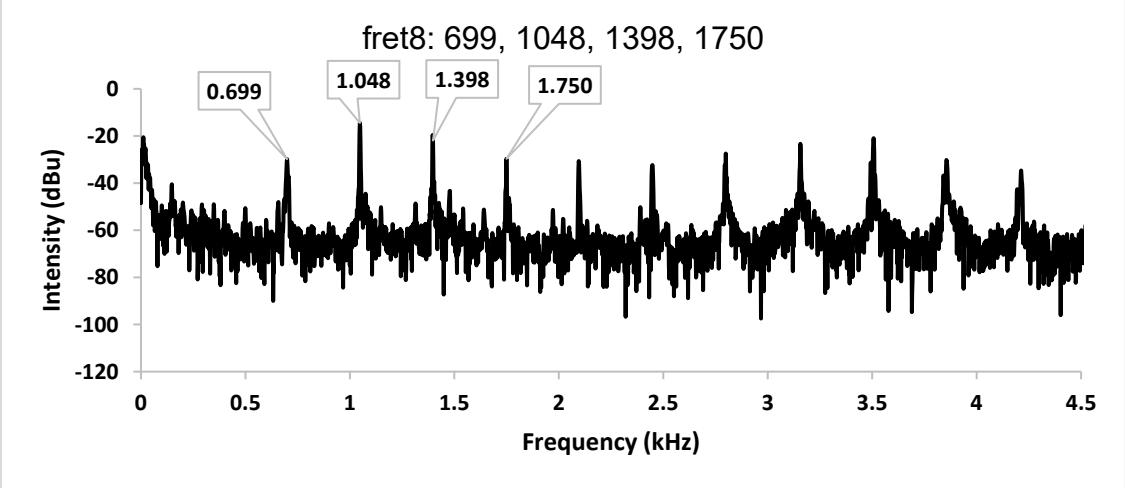


Fig. A1h. Fret 8: 699 (F5), 1048 (C6), 1398 (F6), 1750 (A6)

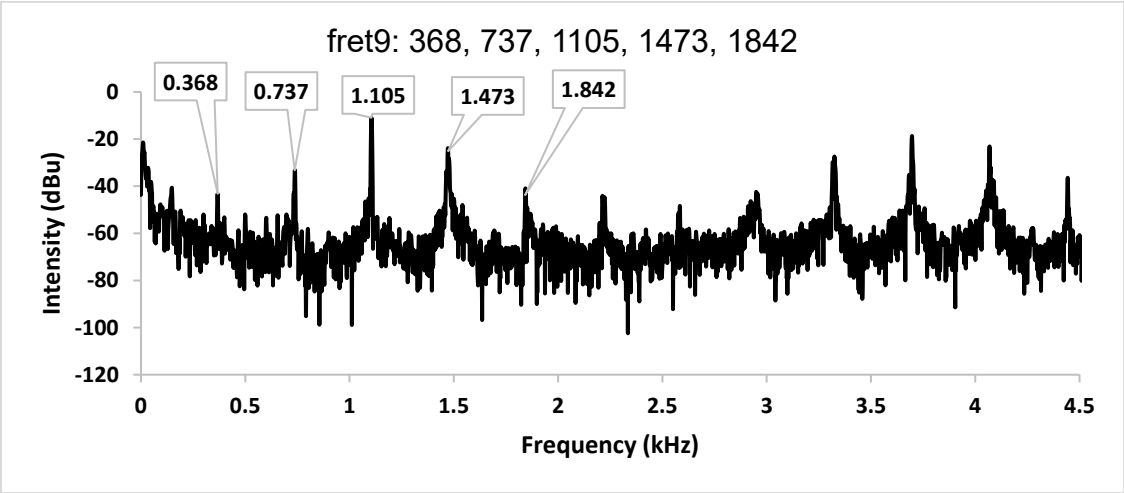


Fig. A1i. Fret 9: 368 (F4♯), 737 (F5♯), 1105 (C6♯), 1473 (F6♯), 1842 (A6♯)

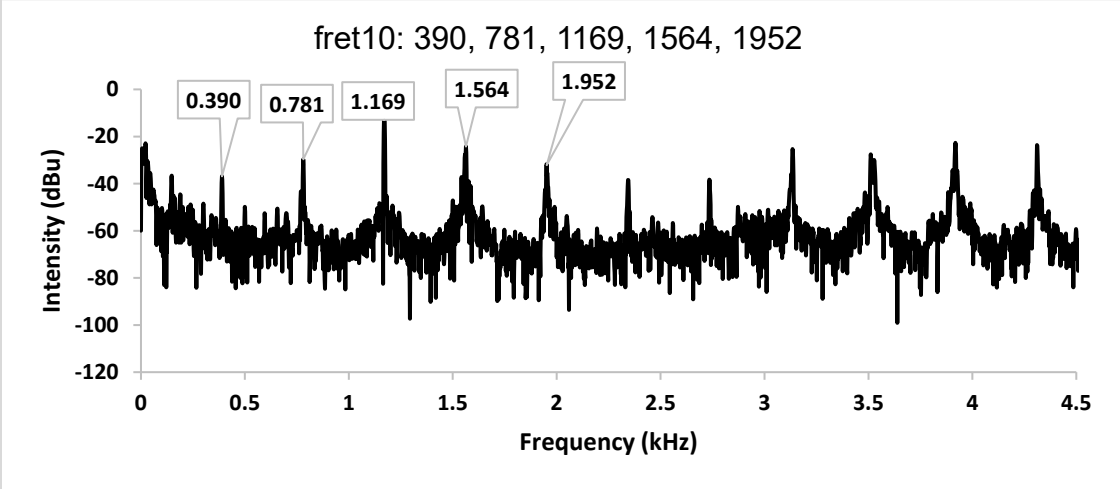


Fig. A1j. Fret 10: 390 (G4), 781 (F5♯), 1169 (D6), 1564 (G6), 1952 (B6)

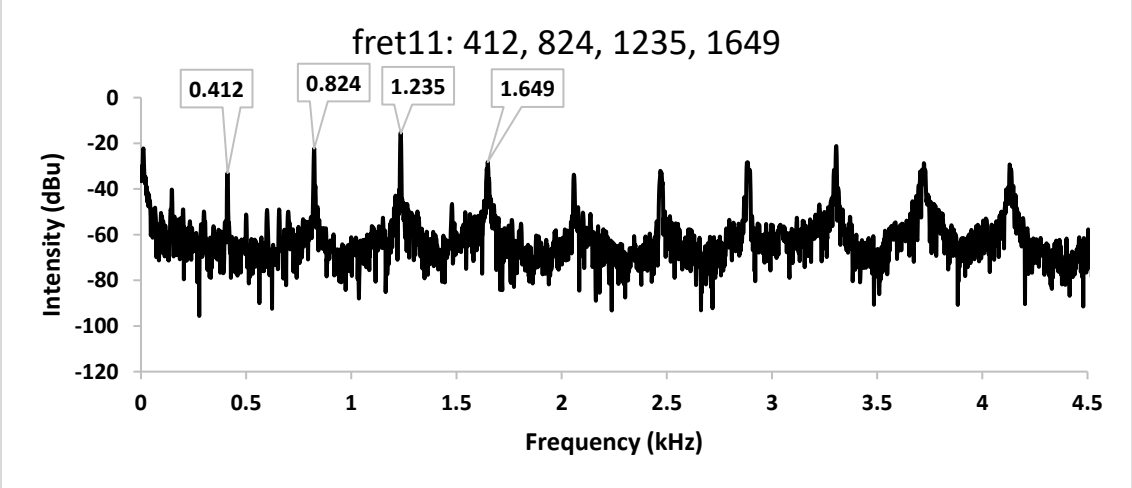


Fig. A1k. Fret 11: 412 (G4♯), 824 (G5♯), 1235 (D6♯), 1649 (G6♯)

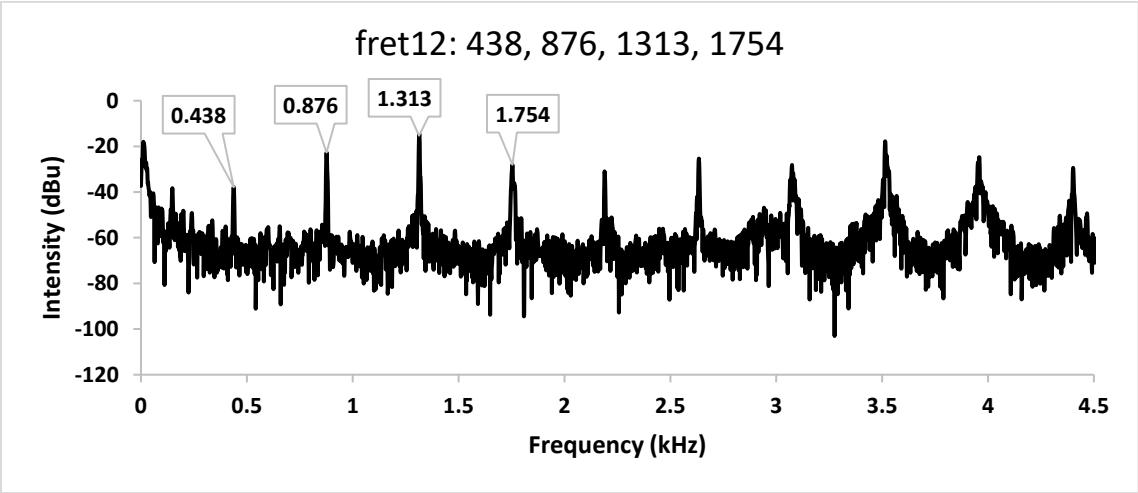


Fig. A1l. Fret 12: 438 (A4), 876 (A5), 1313 (E6), 1754 (A6)

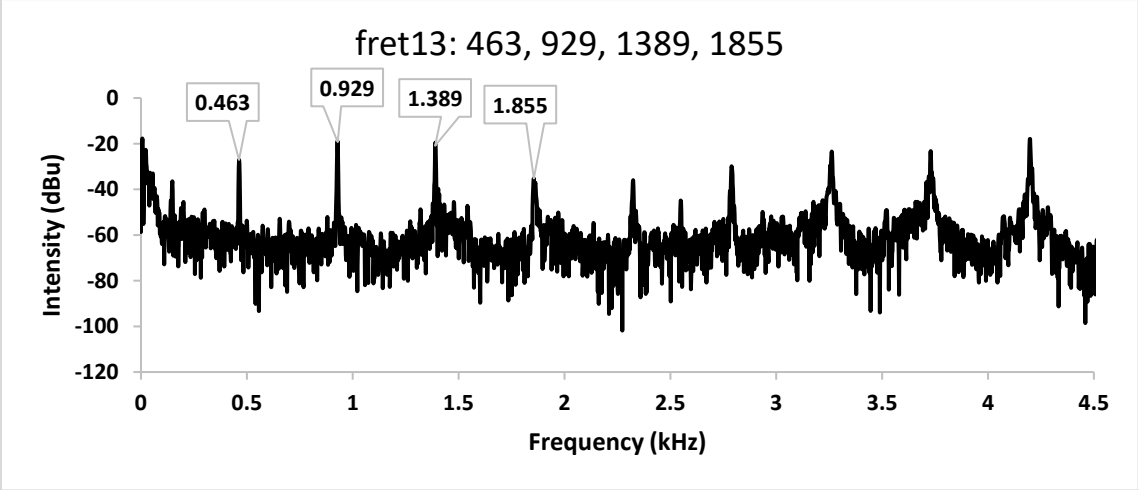


Fig. A1m. Fret 13: 463 (A4♯), 929 (A5♯), 1389 (F6), 1855 (A6♯)

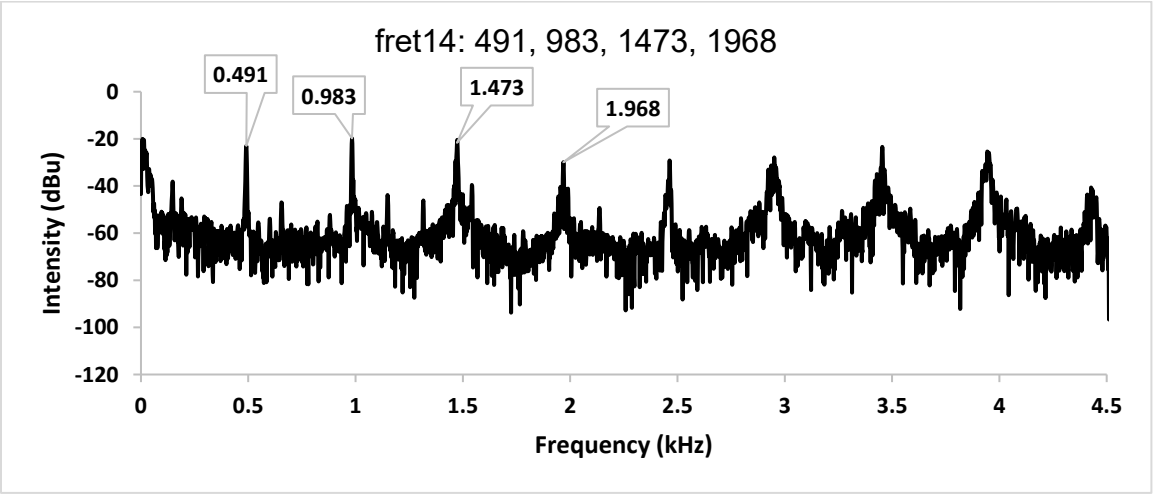


Fig. A1n. Fret 14: 491 (B4), 983 (B5), 1473 (F6♯), 1968 (B6)

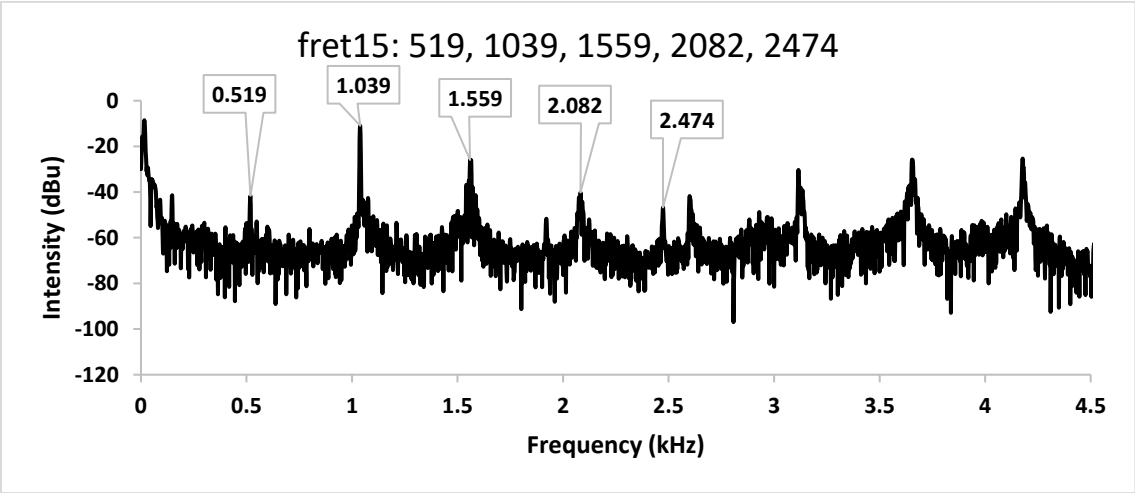


Fig. A1o. Fret 15: 519 (C5), 1039 (C6), 1559 (G6), 2082 (C7), 2474 (D7♯)

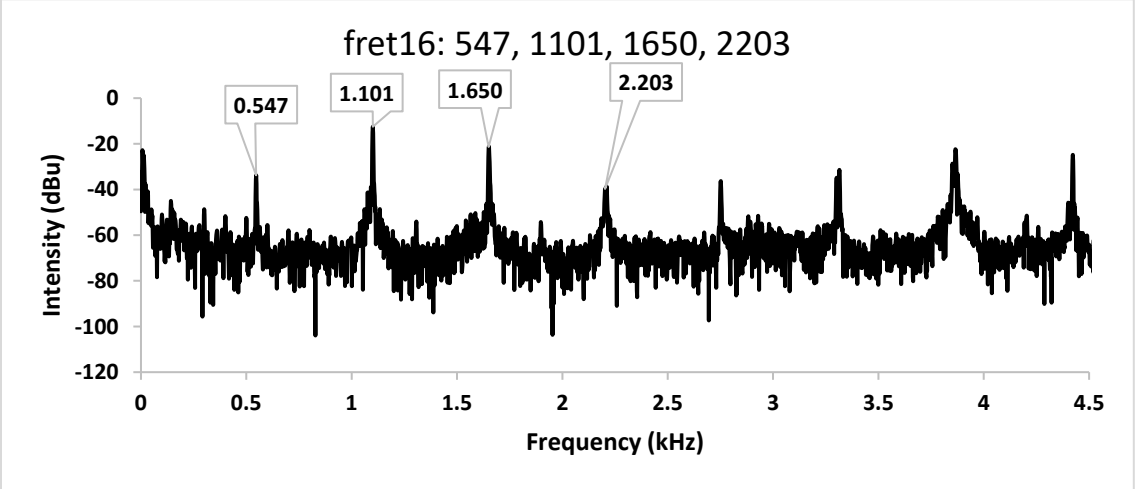


Fig. A1p. Fret 16: 547 (C5♯), 1101 (C6♯), 1650 (G6♯), 2203 (C7♯)

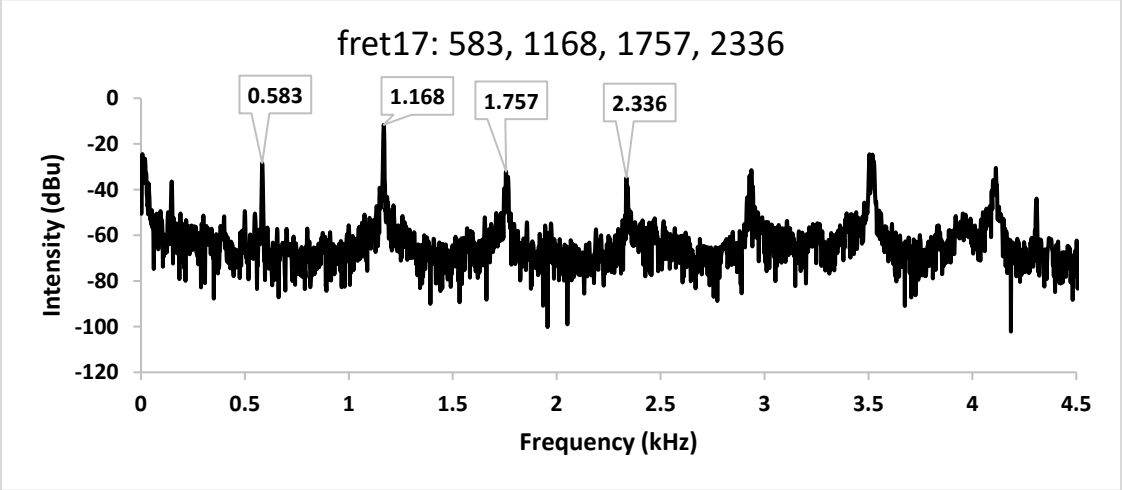


Fig. A1q. Fret 17: 583 (D5), 1168 (D6), 1757 (A6), 2336 (D7)

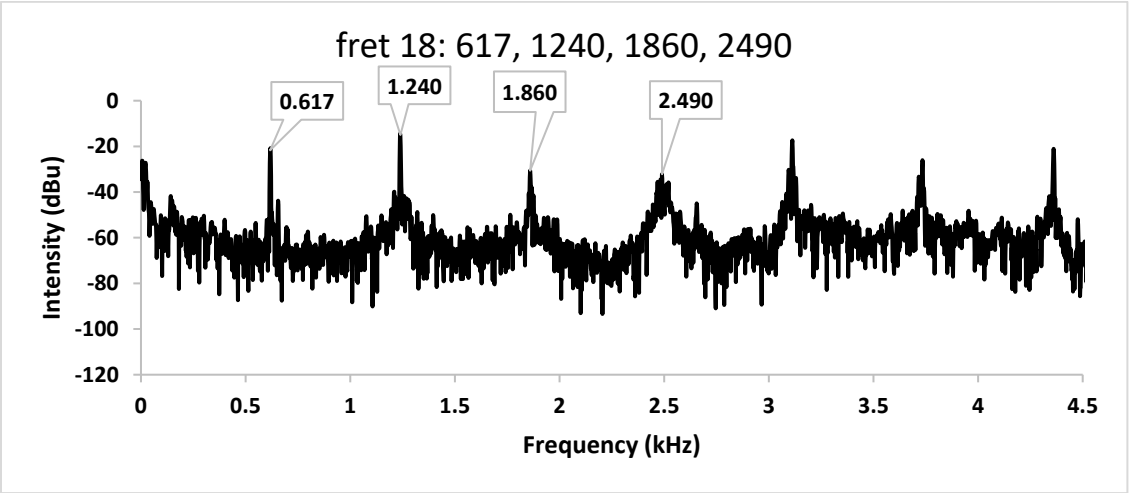


Fig. A1r. Fret 18: 617 (D5♯), 1240 (D6♯), 1860 (A6♯), 2490 (D7♯)

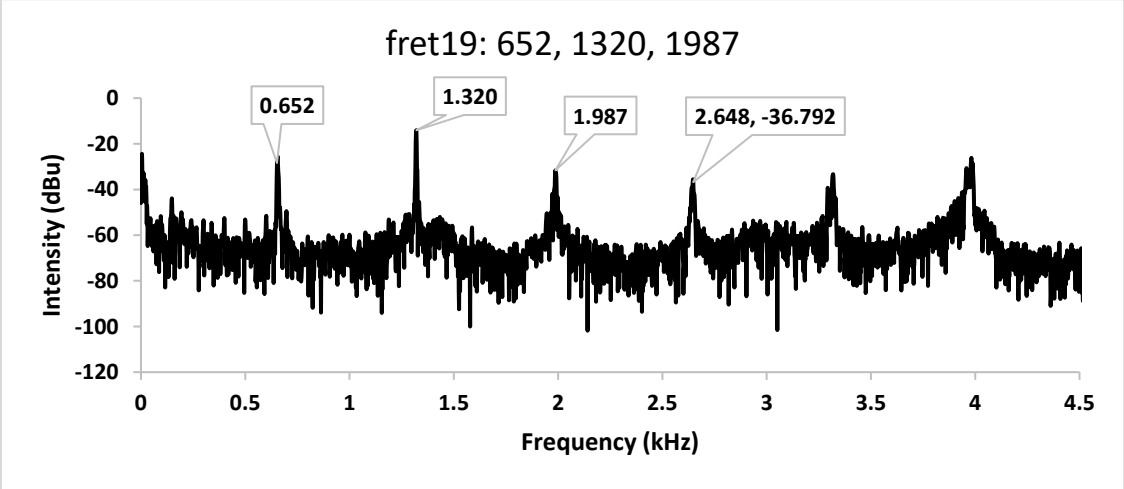


Fig. A1s. Fret 19: 652 (E5), 1320 (E6), 1987 (B6)

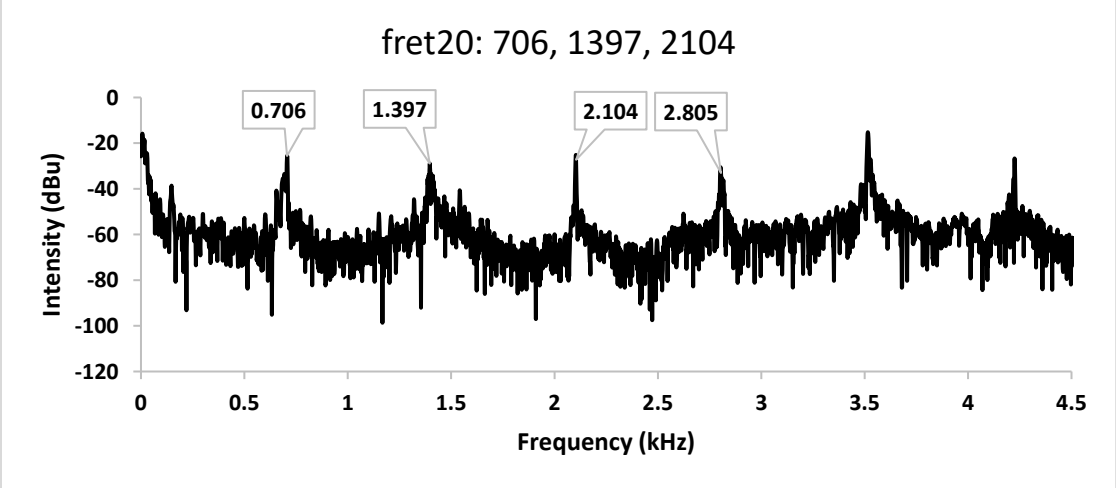


Fig. A1t. Fret 20: 706 (F5), 1397 (F6), 2104 (C7)

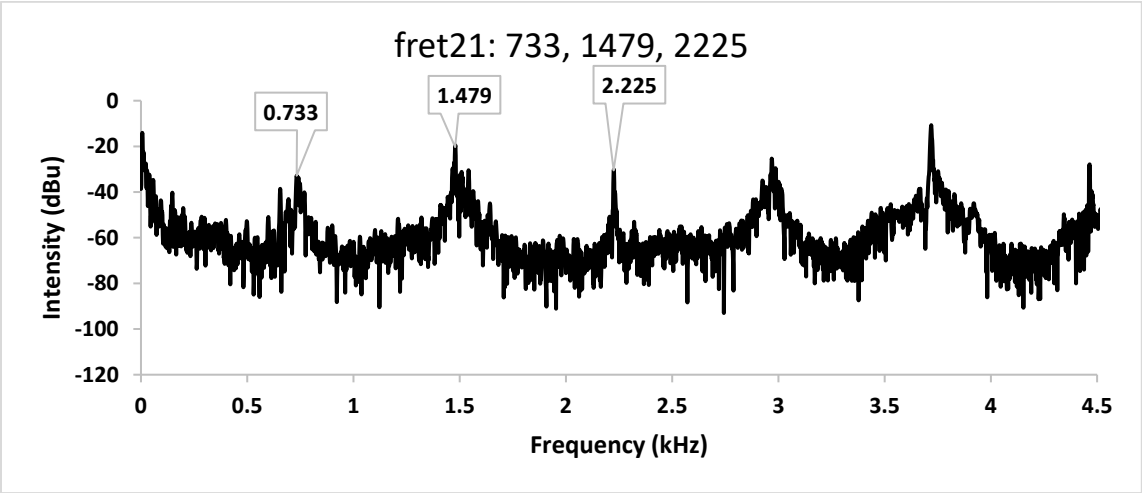


Fig. A1u. Fret 21: 733 (F5♯), 1479 (F6♯), 2225 (C7♯)

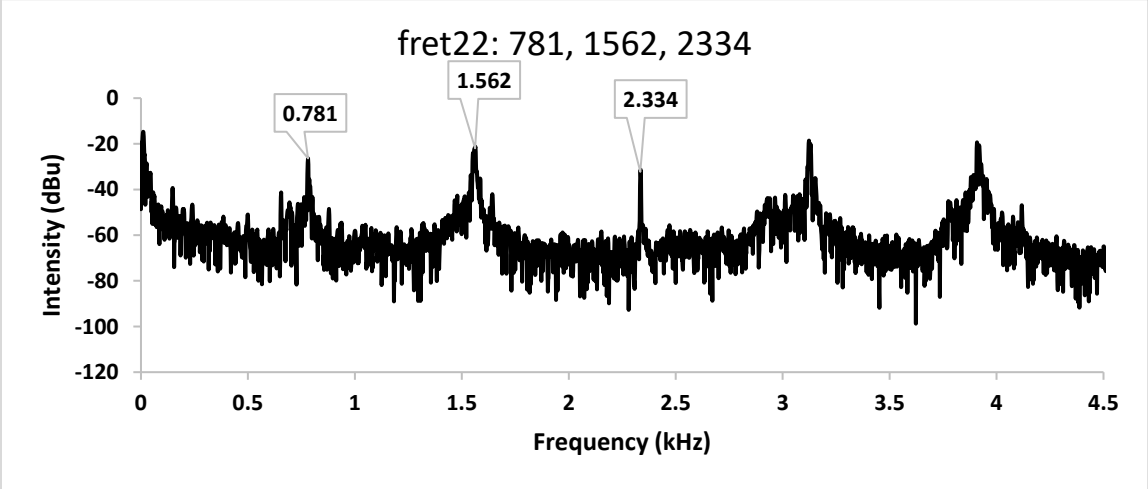


Fig. A1v. Fret 22: 781 (G5), 1562 (G6), 2334 (D7)

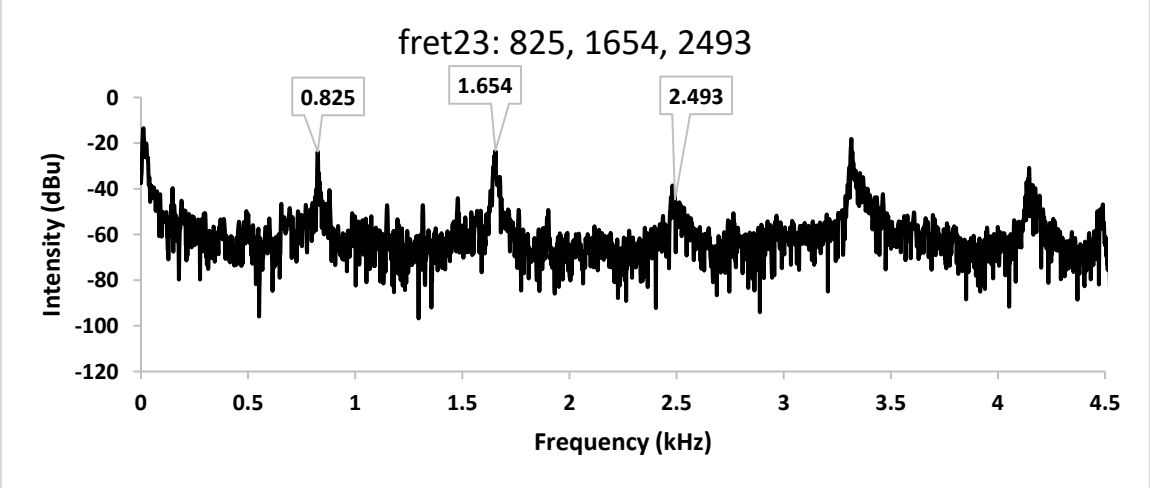


Fig. A1w. Fret 23: 825 (G5♯), 1654 (G6♯), 2493 (D7♯)

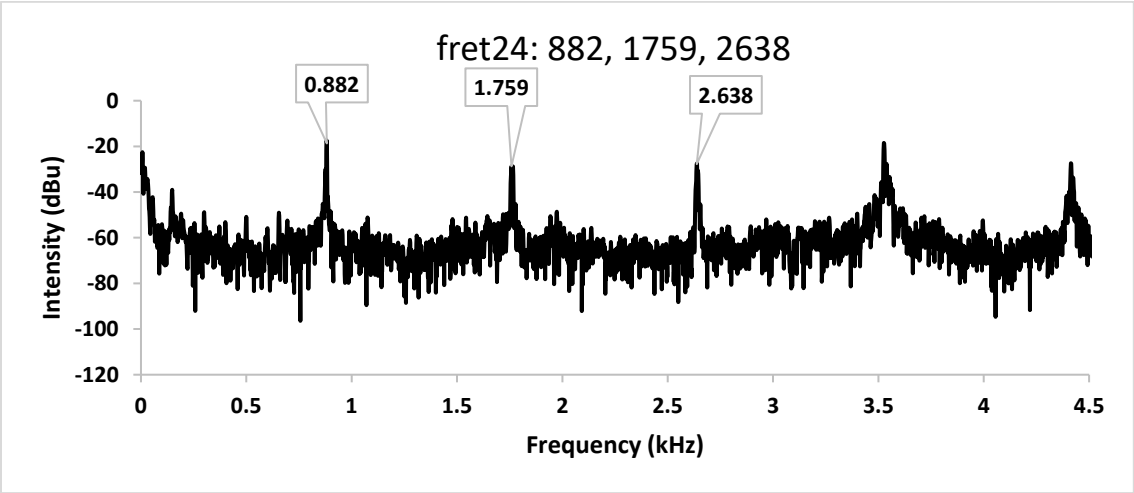


Fig. A1x. Fret 24: 882 (A5), 1759 (A6), 2638 (E7)

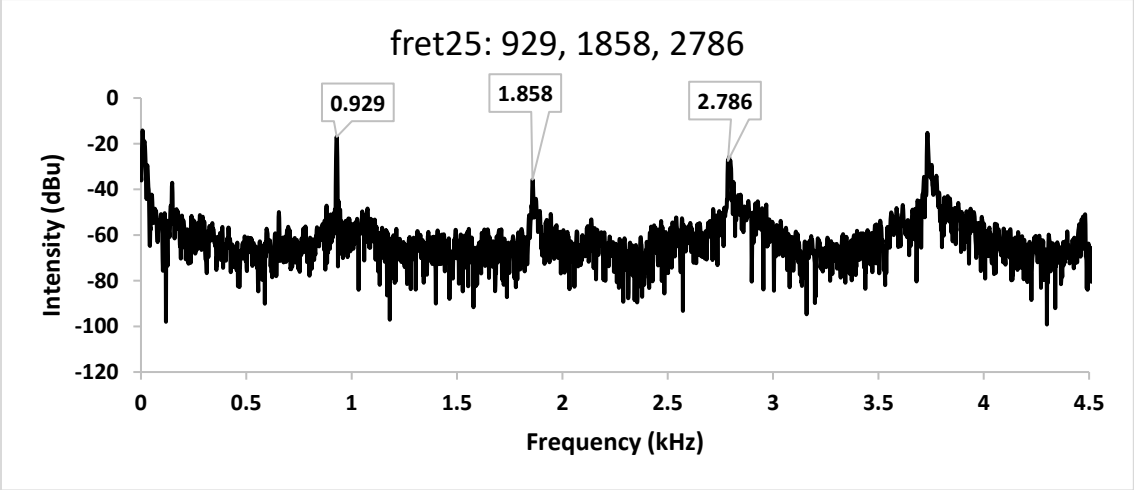


Fig. A1y. Fret 25: 929 (A5♯), 1858 (A6♯), 2786 (F7)

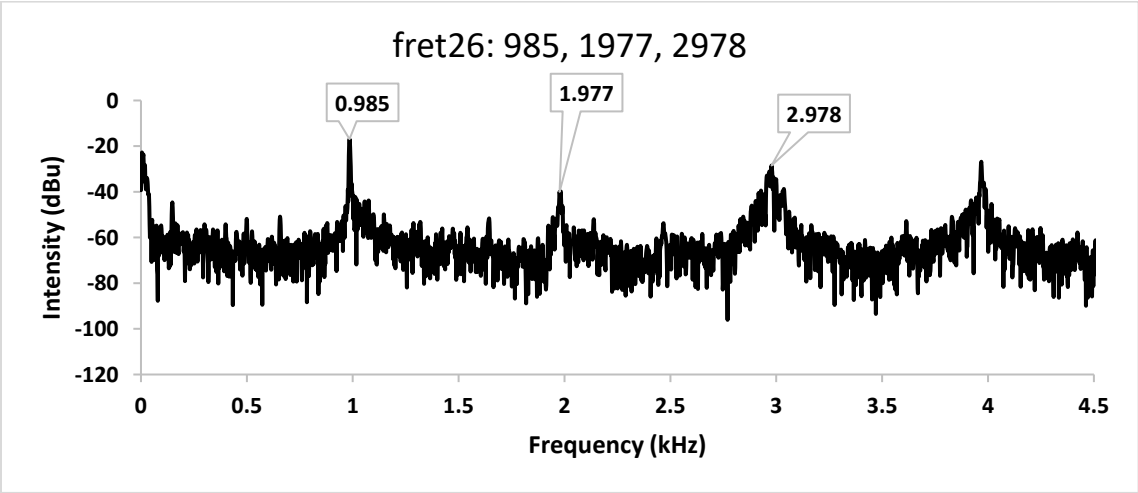


Fig. A1z. Fret 26: 985 (B5), 1977 (B6), 2978 (F7♯)

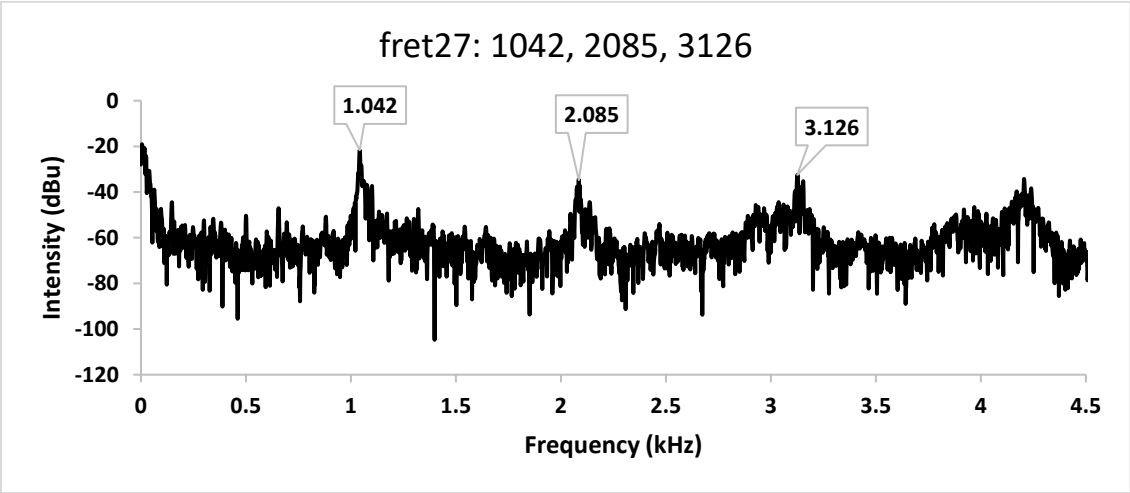


Fig. A1aa. Fret 27: 1042 (C6), 2085 (C7), 3126 (G7)

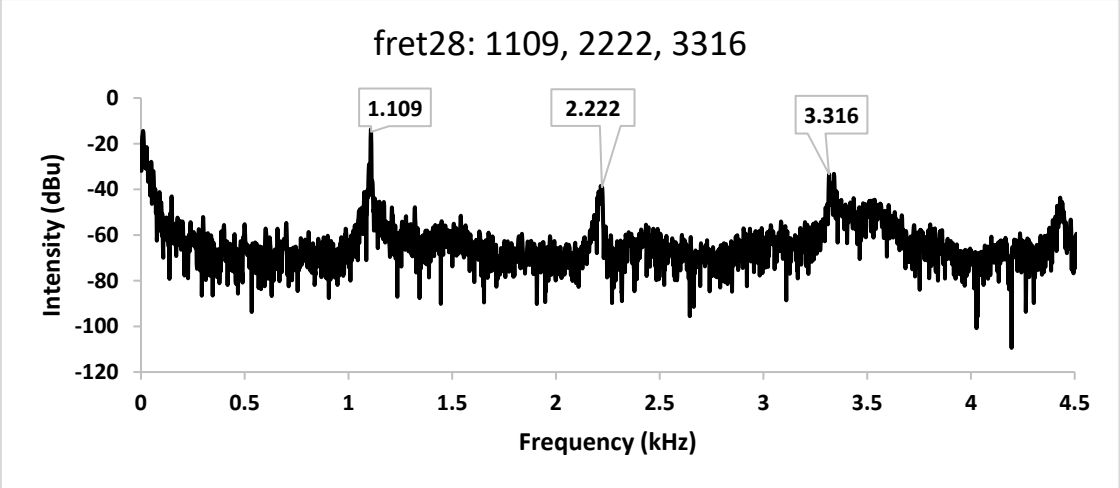


Fig. A1ab. Fret 28: 1109 (C6♯), 2222 (C7♯), 3316 (G7♯)

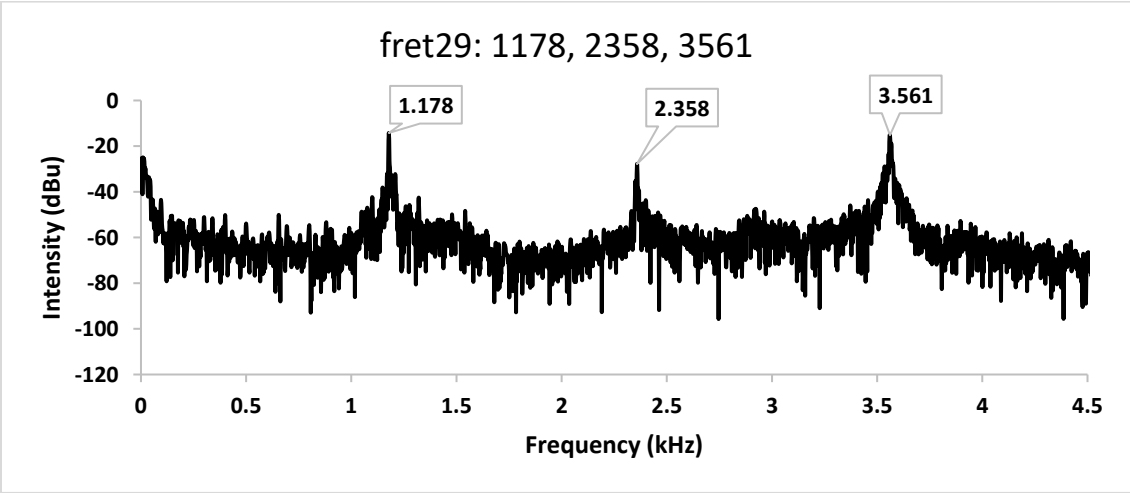


Fig. A1ac. Fret 29: 1178 (D6), 2358 (D7), 3561 (A7)

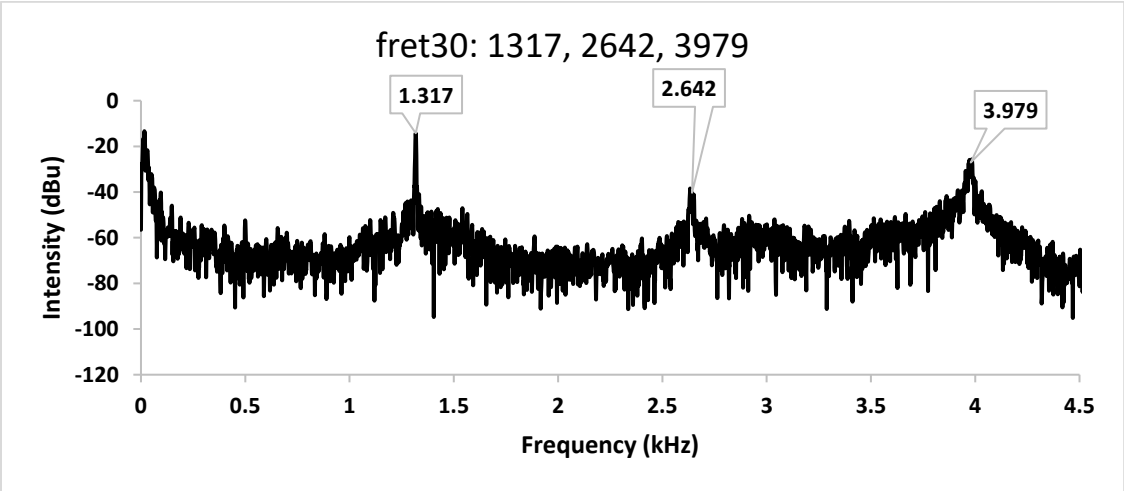


Fig. A1ad. Fret 30: 1317 (E6), 2642 (E7), 3979 (B7)