

Harmonics of Solar Radio Spikes at Metric Wavelengths

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Abstract This paper presents the latest observations from the newly built solar radio spectrograph at the *Chashan Solar Observatory*. On July 18, 2016, the spectrograph records a solar spike burst event, which has several episodes showing harmonic structures, with the second, third, and fourth harmonics. The lower harmonic radio spike emissions are observed later than the higher harmonic bands, and the temporal delay of the second (third) harmonic relative to the fourth harmonic is about 30–40 (10) ms. Based on the electron cyclotron maser emission mechanism, we analyze possible causes of the temporal delay and further infer relevant coronal parameters, such as the magnetic field strength and the electron density at the radio source.

Keywords Radio burst · Dynamic spectrum · Radio spike · Electron cyclotron maser emission

1. Introduction

On the solar radio dynamic spectrum, spikes are narrowband bursts with a typical relative bandwidth of about 1–3% and a duration < 100 ms. Major observational features are as follows: narrowband type III-like storms, spikes, dots, sub-second clusters, groups and chains, and other narrowband structures (Benz, 1986; Bouratzis *et al.*, 2015, 2016). Radio spikes often present as fine structures in the continuum of type IV bursts.

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Radio spikes are closely related to the process of energy release in solar flares and can be used to infer coronal parameters and the energy release process such as magnetic reconnection. Since the discovery of radio spikes in 1961, they have been extensively studied from decimeter to decameter wavelengths (*e.g.* Benz, 1986; Fleishman and Mel'nikov, 1998; Chernov, 2011; Melnik *et al.*, 2014; Bouratzis *et al.*, 2015, 2016; Shevchuk *et al.*, 2016).

At metric wavelengths the typical duration of radio spikes is 10–100 ms, the bandwidth is 0.5–15 MHz (with a relative bandwidth being $\approx 2\%$), the degree of circular polarization is high, and the spectral drift rate can be either positive, negative, or not polarized. Recently, Bouratzis *et al.* (2016) studied 12000 metric radio spikes using observational data from the ARTEMIS-Jean Louis Steinberg Radiospectrograph (ARTEMIS-IV) with a temporal resolution of 10 ms and a frequency range of 270–450 MHz, and found that the duration of these events was 60 ms and the average relative bandwidth was 2%. They also presented the U-shaped, J-shaped, point-like, and cluster-chain spikes.

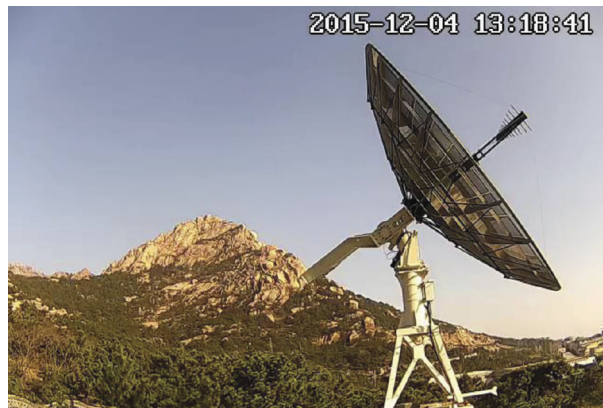
Harmonic structures of spikes were reported for the first time by Benz and Guedel (1987). They studied 36 events of radio spikes using observational data of the Zurich analog spectrograph with a frequency range of 100–1000 MHz and a time resolution of 25–100 ms, and found that for one event there are two emission bands at different frequencies that have a similar morphology. The frequency ratio of the two emission bands is 1:1.39. It is suggested that these two emission bands correspond to different harmonics. Later, Guedel (1990) and Krucker and Benz (1994) also studied the harmonic characteristics of spikes. Guedel (1990) analyzed the data observed by two frequency-agile receivers near Zurich with a frequency range of 100–3000 MHz and a temporal cadence of 50–250 ms. In the paper, the author gave an example of harmonic structures in nine episodes of solar radio spikes between 1980 and 1990. It is found that the harmonics are not limited to the second and third orders, but that the fifth, sixth, or even eighth harmonic orders also exist. The fundamental (not detected) frequency of these events lies in the range of 170–350 MHz. The intensity of the radio spikes becomes stronger with increasing harmonic orders. The author also attempted to measure the time delay of lower harmonics relative to higher harmonics, and found that the delay was likely less than 50 ms. This is below the temporal resolution of the observational data. Therefore, the exact delay of the lower-relative-to higher harmonics could not be determined.

The ARTEMIS-IV data have a higher temporal resolution (10 ms). The observing band extends from 270 to 450 MHz, however, which is too narrow to observe the full harmonics of radio spikes. This is probably the reason why Bouratzis *et al.* (2015, 2016) did not observe any harmonic structures of radio spikes.

The temporal delay of the lower-relative-to higher harmonics of radio spikes is yet to be determined. The observational data available so far that were used in the study of radio spike harmonic structures have been observed in the 1970s and 1980s. The frequency range and the time resolution of these data are somewhat insufficient to measure the relative timings of various harmonic structures.

In this paper, we use the latest data from a new solar radio dynamic spectrograph working at metric wavelengths to study solar radio spike harmonic structures. The following section describes the instrument and data. In the third section, we present the observational characteristics of the event. In the fourth section, we discuss possible causes of the time delay of lower-order harmonics. A summary is presented in the last section.

Figure 1 CSO 6-meter parabolic dish and the dual-polarized log-periodic antenna feed.



2. Observational Data and Instrument

In this paper, we mainly use the data from the solar radio dynamic spectrograph at the *Chashan Solar Observatory* (CSO). The station is located at 122.3°E and 36.8°N , and is constructed and managed by the *Institute of Space Sciences of Shandong University*. On its northern side, there is the Chashan mountain, extending along the east–west direction at a height of more than 500 meters above sea level, and on the southern side, the observatory faces the Yellow Ocean. The mountain blocks a significant part of broadcast communication signals and other radio interferences from the city. Therefore, the radio frequency interference is at a relatively low level. This makes the station highly suitable for observations of solar radio bursts at metric wavelengths.

The newly built solar radio observational system includes a 6-meter parabolic dish fed by a dual-polarized log-periodic antenna as shown in Figure 1. The observing band is 150–500 MHz and the beam size is 12° at 300 MHz. The received signals are filtered, amplified, and sampled by an AD converter, and then a fast Fourier transform (FFT) analysis is performed with a high-speed field programmable gate array (FPGA). The resolutions of the obtained radio dynamic spectral data are 10 ms and 160 kHz, and the dynamic range is ≈ 50 dB. Du *et al.* (2017) reported the technical details of the data acquisition and recording. In order to ensure the reliability of the observational data, we also use the data of the ORFEES (<http://radio-monitoring.obspm.fr/downloadOrfeesHR1.php>) and the *Radio Solar Telescope Network* (RSTN)/Learmoth (http://www.sws.bom.gov.au/World_Data_Centre/1/10) for comparison.

The solar radio burst occurred on July 18, 2016. The associated active region was located at N05W03, and the soft X-ray flare class was C4.4, with start, peak, and end times of 08:09:00 UT, 08:23:00 UT, and 08:32:00 UT. The radio spikes studied in this article were observed during 08:10:00 UT–08:15:00 UT, in the pre-impulsive phase of the flare. Figures 2a and 2b show the solar radio dynamic spectra of these spikes recorded by ORFEES and the CSO. For comparison, ORFEES and CSO data are adjusted to the same time resolution and frequency range. Obviously, the radio dynamic spectra from these two stations are basically the same. The spectra contain many narrowband spikes superposed onto a type IV continuum burst.

To further confirm the accuracy of the observed data, we compared the CSO data with the calibrated RSTN/Learmoth (LEAR) data. RSNT/LEAR can provide solar observation data at ten frequencies between 245–15000 MHz, and only the two frequencies of 245 MHz and

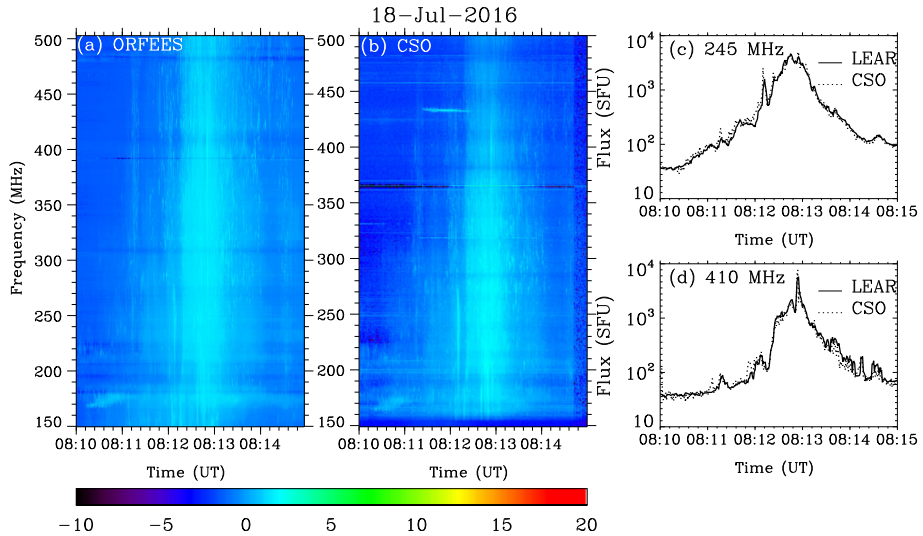


Figure 2 (a, b) Solar radio dynamic spectra recorded by ORFEES and at the CSO at 150–500 MHz. (c, d) Solar radio burst flux density profiles observed at 245 MHz and 410 MHz by the LEAR and CSO. See text for details. The *color bar* indicates the relative intensity (the same below).

410 MHz lie in the CSO observational band. The flux density profiles from LEAR at these two frequencies are shown in Figures 2c–d as solid lines. The recorded signal values R of the CSO at the two corresponding frequencies are adjusted according to the relationship of

$$R' = A \log[(R - B)C], \quad (1)$$

where A and C are mainly determined by the receiver system gain, and B is mainly determined by the receiver system noise. A similar calibration method has been used by Messmer, Benz, and Monstein (1999). We adjusted the values of A , B , and C so as to make the CSO flux density profiles as close as possible to the LEAR profiles. The values R' are shown by dotted lines at the corresponding frequencies in Figures 2c–d. We can make the light curves of the CSO data look basically the same as those of LEAR at the two frequencies. This can be regarded as a preliminary calibration process. Further calibration of the system with calibrated noise sources and signals is under way.

3. Metric Radio Spikes Observed by the CSO

Figure 3 shows a segment of the spectrum with the highest temporal resolution of 10 ms observed by the CSO spectrograph for the solar radio spike event. In this figure, the spike signals look like dense light-drizzle falling from the sky. The duration of each small spike burst is about some tens of milliseconds, and the minimum bandwidth is lower than 10 MHz. Some spike clusters (formed by a group of spikes) appear in the segment, and at certain discrete frequencies, the clusters have similar morphology. For example, the arrows in the figure indicate three rows of spike clusters with similar structures at frequencies of ≈ 200 MHz, 300 MHz, and 400 MHz. There exist many other sets of similar clusters, *e.g.* those at $\approx 08:13:50$ UT, at ≈ 270 MHz and ≈ 360 MHz.

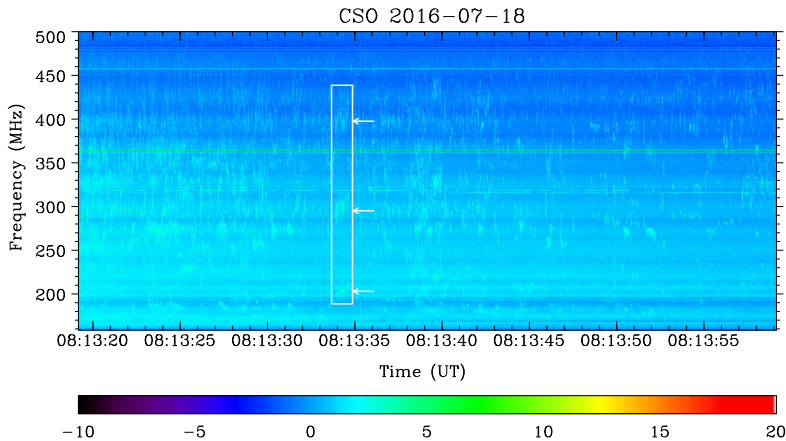


Figure 3 Solar radio spikes observed by the CSO spectrograph at metric wavelengths. The temporal resolution of the data is 10 ms. The white rectangular box indicates three rows of solar radio spike clusters with similar structures at 200 MHz, 300 MHz, and 400 MHz, as indicated by the white arrows.

3.1. Harmonic Structures of Spike Clusters

Four sets of spike clusters with similar structure at different frequencies are shown in Figures 4a–b and Figures 5a–b. Figure 4a displays a high-resolution (10 ms and 160 kHz) dynamic spectrum of one radio spike cluster. The figure clearly shows two rows of spike clusters (also called spike chains). The frequency ranges of these two chains are 390–403 MHz and 285–298 MHz, indicated by two dashed (H4) and two dotted line pairs (H3), respectively. Their central frequencies are 396 MHz and 291 MHz, and the frequency ratio is ≈ 1.36 . The spike clusters within the two frequency ranges match well.

To quantitatively analyze the correlation between the H3 and H4 spike cluster chains, we integrated the signal strength of spikes within H3 and H4, and normalized the integrated intensities. The obtained light curves are shown in the upper part of Figure 4c, labeled L3 for H3 and L4 for H4. The peaks of these two light curves basically manifest a one-to-one correspondence. The correlation coefficient (CC) is as high as 0.66. This indicates that the two sets of radio spikes originate from the same energy release and radiation process. In addition, the ratio of the central frequency of the two groups is about 1.36, which is very close to 4:3 and implies that the H4 and H3 spike chains are the fourth and third harmonics of a single spike emission.

Previous studies have implied that the occurrence of lower harmonics has a certain time delay relative to higher harmonics for solar radio spikes (Guedel, 1990). The spike event observed here consists of two clear cluster chains and has been observed with a high temporal resolution, thus is suitable for further quantitative measurement of the delay. The light curve of L3 is shifted forward or backward by ΔT (because the time resolution is 10 ms, ΔT is set to be one to several 10 ms). When the light curve of L3 is shifted forward by $\Delta T = 10$ ms, the correlation coefficient between the adjusted light curve of L3 (referred to as L3') and L4 reaches a maximum value of $CC' = 0.79$. This indicates that the third harmonic emission is observed $\Delta T_{34} \approx 10$ ms later than the fourth harmonic band. Since the temporal resolution of the data is 10 ms, the time delay between the third harmonic and the fourth harmonic should be in the range of 5 ms and 15 ms. Data with a higher temporal resolution are required to further determine the exact value of the delay.

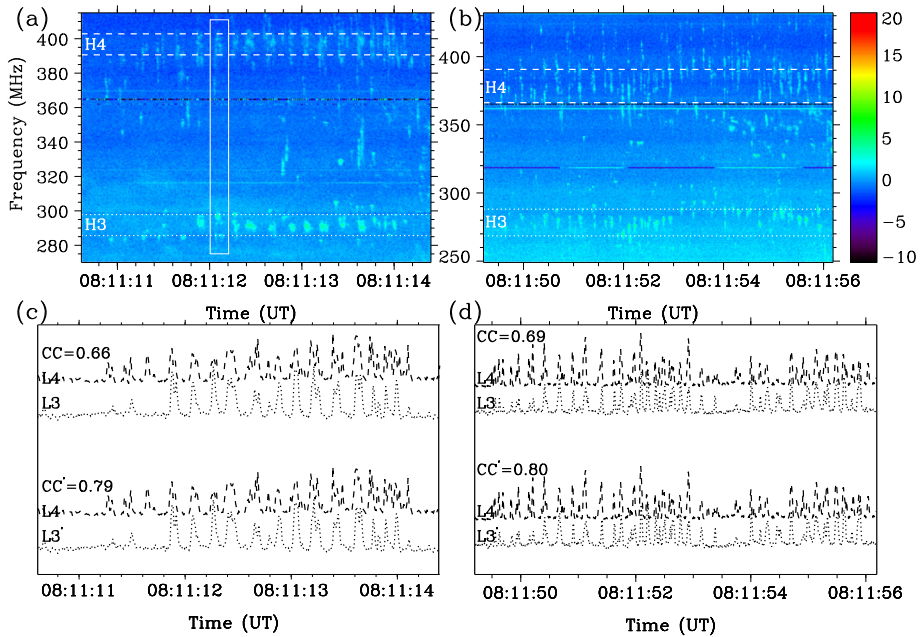


Figure 4 (a, b) Spectra of two sets of solar radio spike clusters with the third and fourth harmonics. The dotted (H3) and dashed line pairs (H4) are used to indicate two spike clusters with similar morphology. (c) Dotted (L3) and dashed profiles (L4) show the light curves of integration and normalization of the radio spike burst intensity between the two line pairs (H3 and H4), and L3' is the light curve of L3 shifted forward by 10 ms. (d) Profiles are the same as those in (c), but obtained from the spectrum of (b).

For the radio spike in Figure 4b, we conducted a similar analysis. The two dotted (H3) and dashed (H4) lines outline the frequency range of 366–390 MHz and 268–289 MHz, respectively, and the central frequency ratio is 1.37. In Figure 4d the correlation coefficient CC between the light curves of L3 and L4 is 0.69, and it becomes as high as 0.8 after L3 is shifted forward by 10 ms. For this row of spike chains, the time delay of the third relative to the fourth harmonic is also between 5 ms and 15 ms.

In the dynamic spectrum of Figure 5a, the two solid, dotted, and dashed lines indicate three rows of radio spikes within the frequency range of 190–215 MHz, 290–330 MHz, and 380–430 MHz, and the ratio of the central frequency is 1:1.5:2, which corresponds to the second, third, and fourth harmonic emission, respectively. The normalized light curves within the corresponding frequency band of the three groups are plotted with solid, dotted, and dashed lines in Figures 5c–e, respectively. The correlation coefficient between the second and third (the second and fourth, and third and fourth) harmonics is 0.29 (0.25 and 0.64). When the light curves of the second and third harmonics are shifted forward by 30 ms and 10 ms, respectively, the correlation coefficient increases to a maximum value of 0.58 (0.8) between the second and third harmonic bands (the third and fourth). When the light curve of the second harmonic is moved forward by 40 ms, the correlation between the light curves of the second and fourth harmonics is 0.54. Figure 5b shows another group of radio spikes with the second, third, and fourth harmonics. We also performed a similar analysis and list the results in Table 1 together with those of the former three groups of harmonic structures.

From Table 1, we can see the fundamental frequencies of spikes are all ≈ 100 MHz (not observed). Based on the ECM mechanism, the magnetic field strength at these spike sources

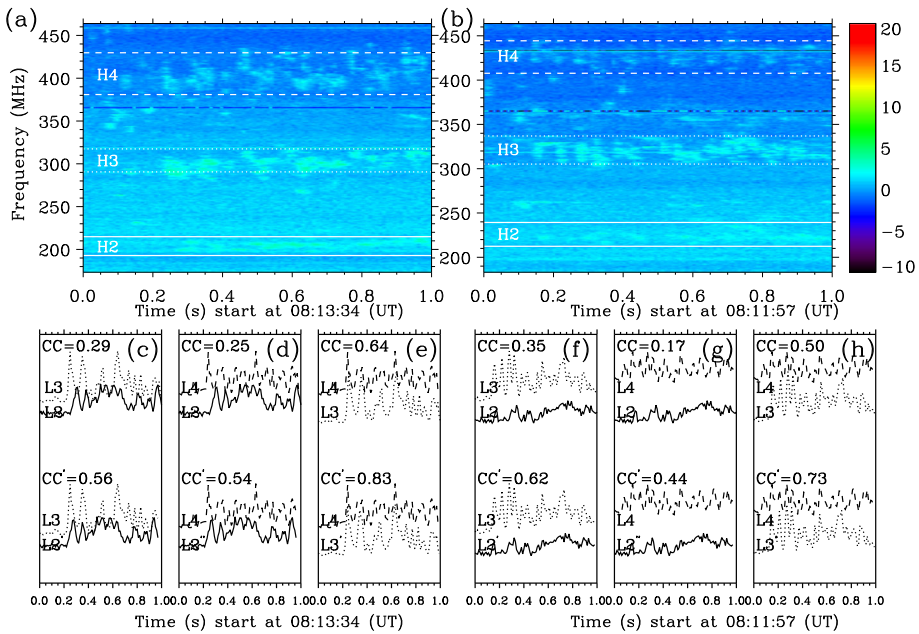


Figure 5 (a, b) Spectra of two sets of solar radio spike clusters with the second, third, and fourth harmonics. The *solid* (H2), *dotted* (H3), and *dashed* line pairs (H4) are used to indicate three spike clusters with similar morphology. (c–e) *Solid* (L2), *dotted* (L3), and *dashed* profiles (L4) show the light curves of integration and normalization of the radio spike burst intensity between the two line pairs (H2, H3, and H4), and L2', L2'', and L3' are the light curves of L2, L2, and L3 shifted forward by 30 ms, 40 ms, and 10 ms. (f–h) Profiles are the same as those in (c–e), but obtained from the spectrum of (b), and L2', L2'', and L3' are the light curves of L2, L2, and L3 shifted forward by 20 ms, 30 ms, and 10 ms.

Table 1 Parameters of four sets of solar radio spike clusters with harmonic structures. Occurrence time, duration, central frequency, central frequency ratio, fundamental frequency, and time delay between different harmonic emissions are given in Columns 1 to 8, respectively.

Time (UT)	Duration (s)	Central freq. (MHz)	Ratio	Fund. freq. (MHz)	Delay (ms)		
					ΔT_{23}	ΔT_{24}	ΔT_{34}
08:11:10	3.5	390, 395	3:4	97	—	—	10
08:11:48	7	285, 390	3:4	95	—	—	10
08:11:56	1	210, 315, 420	2:3:4	105	30	40	10
08:13:34	1	200, 300, 400	2:3:4	100	20	30	10

is about 36 G with

$$\Omega_{ce} = \frac{eB}{m_e c} = 1.759 \times 10^7 B \text{ (rad s}^{-1}\text{)}, \quad (2)$$

in which $e = 4.8 \times 10^{-10}$ ESU(C) is the electron charge, $m_e = 9.1 \times 10^{-28}$ g is the electron mass, B represents the magnetic field strength in Gauss, and $c = 3.0 \times 10^{10}$ cm s $^{-1}$ is the speed of light. This provides a diagnostic of magnetic field strength in the radio source region.

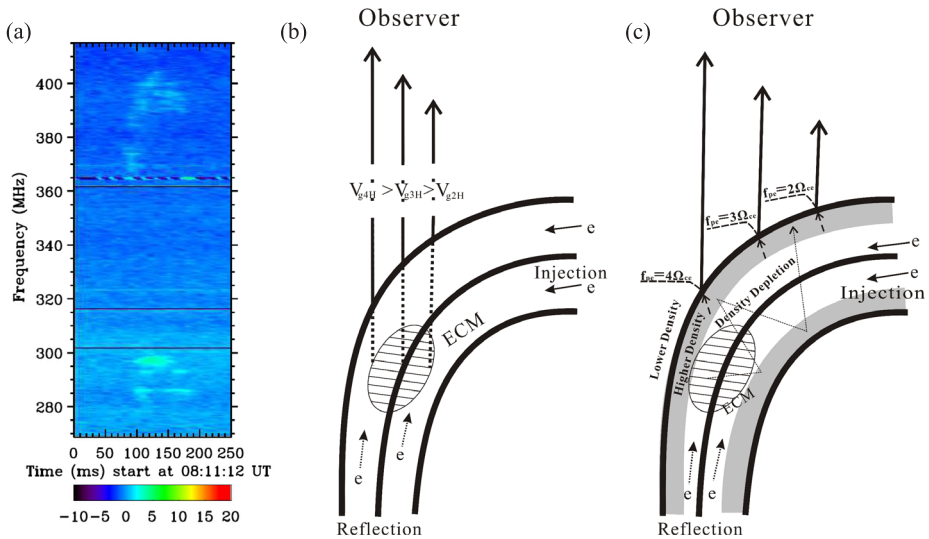


Figure 6 (a) Radio spectrum of the inverted V-shape radio spike clusters. (b, c) The schematics for the causes of the temporal delay of the lower harmonics relative to higher orders and the formation of inverted V-shape clusters. Energetic electrons accelerated from magnetic field reconnection are injected into the magnetic loop system, and because of the magnetic mirror effect, the electrons are reflected above the magnetic loop foot point. Electrons with different distributions are unstable and can efficiently drive ECM. The injected and reflected electrons result in the emission of the first and second branches of the inverted V-shape spike cluster, respectively. (b) The group velocities of the second, third, and fourth harmonics are different ($V_{g4H} > V_{g3H} > V_{g2H}$) and this difference can cause the time delay. (c) When the ECM emission propagates in a central density-depleted magnetic loop (the surface density is higher and the surrounding density is lower), the fourth harmonic escapes at the lower site with the plasma frequency $f_{pe} = 4\Omega_{ce}$, and the third and second harmonics escape at relatively higher sites of the magnetic loop structures, and the plasma frequencies are $3\Omega_{ce}$ and $2\Omega_{ce}$. Therefore the lower harmonics take longer to escape from the magnetic loop.

3.2. Periodic and Inverted V-shape Spike Clusters

In Figures 4a and 4b (08:11:50–08:11:52 UT), the occurrence of the solar radio spikes shows a clear periodicity. This periodicity is better seen in the light curves. There are a total of ≈ 10 radio peaks within 2 s in Figure 4c and ≈ 15 peaks within 3 s in Figure 4d (08:11:50–08:11:53 UT). The occurrence period of the peaks is ≈ 0.2 s. We used a wavelet analysis to analyze the two series of light curves, and confirm that the occurrence period is 0.2 s. The confidence level of the periodic analysis is higher than 95%.

In addition, almost all of the radio spike clusters in Figure 4a are composed of two branches of spikes, and the light curves in Figure 4c also present a double-peak morphology. In Figure 4a the white rectangle indicates two sets of spike clusters with clear dual-branch structure. The radio spectrum in the white rectangular box is enlarged and shown in Figure 6a.

Figure 6a shows that in both clusters the frequency first increases and then decreases, forming an inverted V structure. The inverted V-shape spike clusters are found in both the third and fourth harmonics. The start frequency of the fourth harmonic is 365 MHz, and after 50 ms, it rises to 405 MHz; 50 ms later, the frequency decreases to 387 MHz. We can obtain that the frequency drift rate is about 800 MHz s^{-1} and -360 MHz s^{-1} for the rising and decreasing parts of the spike cluster, respectively. These values are comparable to those of typical type III bursts.

The peak frequency of the fourth harmonic of the inverted V-shape spike cluster is about 400 MHz, and the corresponding electron cyclotron frequency Ω_{ce} is about 100 MHz. The inferred maximum magnetic field strength at the radio spike source is also 36 G.

4. Discussion

Two major emission mechanisms (Benz, 1986) have been proposed to explain solar radio spikes. One is the plasma emission mechanism. This involves enhanced Langmuir waves induced by the bump-on-tail instability caused by beams of energetic electrons through a complex wave–wave coupling process. These Langmuir waves are then converted into electromagnetic radiation escaping from the source region at the plasma oscillation frequency and its harmonics. The other mechanism is the electron cyclotron maser (ECM) mechanism. In a magnetic structure filled with energetic electrons injected by energy release processes in solar eruptions, some electrons with a relatively higher parallel velocity (smaller pitch angle) may propagate down to the solar surface and escape from the magnetic structure. This may give rise to an electron velocity distribution function that is capable of exciting the ECM (Wu and Lee, 1979; Wu, 1985; Fleishman and Mel’nikov, 1998; Ergun *et al.*, 2000; Bingham *et al.*, 2013), releasing electromagnetic waves with a frequency close to the electron cyclotron frequency of Ω_{ce} or/and its harmonics.

The observed characteristics of spike radiation (such as the narrow bandwidth, high polarization, and high brightness temperature) can be explained by the ECM and by the plasma emission mechanism. However, radio spike bursts can sometimes exhibit high-order (6–8) harmonics, which is very difficult to explain with the plasma emission mechanism, and it is generally understood to be a result of the ECM emission (Guedel, 1990). Here, we used the ECM mechanism to understand the observed time delay of the lower harmonics relative to the higher ones of the radio spike at metric wavelengths and the generation of inverted V-shape spikes.

4.1. Causes of the Temporal Delay of the Lower Harmonics

Three possible factors can lead to the delay between lower and higher harmonics (*e.g.* Dorovskyy *et al.*, 2015; Kong *et al.*, 2016). First, the group speed of the lower harmonics is lower than that of higher harmonics, therefore it takes a longer time for the lower harmonics to propagate to Earth from the spike source, as shown in Figure 6b. Second, when we assume that the ECM emission arises from a central density-depleted magnetic loop, as shown in Figure 6c, higher harmonics can radiate out from the lower site of the loop (near the emission-exciting region), while lower harmonics have to propagate to a higher site and take a longer time to escape from the magnetic loop (such as electromagnetic waves propagating in a waveguide). Last, the refraction or reflection of an electromagnetic wave at different frequencies may also result in a time delay of the lower harmonics.

For the first interpretation, the group velocity V_g is determined by

$$V_g = c \sqrt{1 - \left(\frac{f_{pe}}{f} \right)^2}, \quad (3)$$

where $c = 3.0 \times 10^{10} \text{ cm s}^{-1}$ is speed of light, and f represents the observational radio frequency. This frequency is taken to be $f_{2H} = 200 \text{ MHz}$ (the second harmonic), $f_{3H} =$

300 MHz (third), and $f_{4H} = 400$ MHz (fourth). The frequency of f_{pe} is the plasma frequency on the radio emission propagation path. Here,

$$f_{pe} \approx 9000 \sqrt{N_e \text{ (cm}^{-3}\text{)}} \text{ (Hz)} \quad (4)$$

can be deduced using the solar atmosphere electron density model of Newkirk (Newkirk, 1961) at a distance shorter than $2 R_\odot$:

$$N_e = 4.2 \times 10^4 \times 10^{\frac{4.32}{r}} \text{ (cm}^{-3}\text{)}, \quad (5)$$

and through the model developed by Leblanc, Dulk, and Bougeret (1998) for the distance range of $2-215 R_\odot$:

$$N_e = 3.3 \times 10^5 r^{-2} + 4.1 \times 10^6 r^{-4} + 8.0 \times 10^7 r^{-6} \text{ (cm}^{-3}\text{)}, \quad (6)$$

where r is in units of the solar radius ($R_\odot = 6.955 \times 10^{10}$ cm). To remove the jump of the density profiles at the connection ($2 R_\odot$) of the two selected density models, we multiplied the model of Leblanc, Dulk, and Bougeret (1998) by a factor of 3.8.

The time difference of the third and fourth harmonics traveling to Earth is then

$$\Delta T_{34} = \frac{1}{c} \int_{r_0}^{215 R_\odot} \left[\frac{1}{\sqrt{1 - \left(\frac{f_{pe}}{f_{3H}}\right)^2}} - \frac{1}{\sqrt{1 - \left(\frac{f_{pe}}{f_{4H}}\right)^2}} \right] dr, \quad (7)$$

and for the second and fourth harmonics, the time difference is

$$\Delta T_{24} = \frac{1}{c} \int_{r_0}^{215 R_\odot} \left[\frac{1}{\sqrt{1 - \left(\frac{f_{pe}}{f_{2H}}\right)^2}} - \frac{1}{\sqrt{1 - \left(\frac{f_{pe}}{f_{4H}}\right)^2}} \right] dr. \quad (8)$$

In order to estimate the starting height (r_0) of the emission, the following method was used. As we know, only radio bursts with a frequency greater than the plasma oscillation frequency can escape from their source region. The local plasma oscillation frequency can be inferred from the observed radio bursts, and then, the starting heights are deduced based on the solar atmosphere density models, such as the Newkirk (1961) density model. In the event, the radio spike frequencies are above 150 MHz, corresponding to the coronal electron density at $1.15 R_\odot$. The starting heights of radio spikes should be higher than $1.15 R_\odot$. In addition, the fundamental bands with a frequency of ≈ 100 MHz, corresponding to $1.25 R_\odot$, are not detected, therefore the emission heights are lower than $1.25 R_\odot$. This means that the deduced heights of the radio spikes lie in the range of $1.15-1.25 R_\odot$ from the solar center. By inserting the heights and Equations 4, 5, and 6 into Equations 7 and 8, we calculate ΔT_{34} and ΔT_{24} to be 20–10 ms and 90–45 ms, respectively, which is consistent with our observations.

It should be noted that two different coronal density models are combined to calculate the time delay. In the range of $2-215 R_\odot$, the calculated temporal delay is about zero, which means that it is negligible in this range. The temporal delay is mainly produced in the solar atmosphere within $2 R_\odot$ from the solar center.

For the second interpretation, Wu *et al.* (2002, 2005) have used the ECM emission within a magnetic flux tube with a lower electron density in the center to explain the emission properties of type III bursts. The most recent studies have shown that radio spikes can be

produced in large-scale magnetic loops in an active region (Cliver, White, and Balasubramaniam, 2011, Morosan *et al.*, 2016). Here, the cutoff frequency of the electromagnetic wave decreases with increasing altitude. Higher harmonics can radiate out from the density-depleted magnetic loop at a lower site (near the emission-exciting region), while lower harmonics have to propagate farther out to escape, which takes longer.

Figure 6c illustrates that the second, third, and fourth harmonics of $2\Omega_{ce}$, $3\Omega_{ce}$, and $4\Omega_{ce}$ escape from the magnetic loop at different heights. From Table 1, the fundamental frequency of the spike burst is inferred to be about 100 MHz. We obtain that the plasma frequencies at the three heights are 200 MHz, 300 MHz, and 400 MHz (as the mode of electromagnetic wave is unknown, we assumed that the escaping frequency equals the O-mode cutoff frequency, *i.e.* the plasma oscillation frequency). The corresponding electron densities are found to be $4.9 \times 10^8 \text{ cm}^{-3}$, $1.1 \times 10^9 \text{ cm}^{-3}$, and $2.0 \times 10^9 \text{ cm}^{-3}$ at the corresponding escaping sites. These values are consistent with the electron density of the coronal loop given by Xie *et al.* (2017).

In addition to these factors, the effect of refraction and reflection cannot be excluded. The lack of information on the source of the spikes, however, prevents determining which cause is the most relevant. Different causes may even work together.

4.2. Possible Cause of the Inverted V-shape Spike Clusters

As the radio spikes appear during the flare, they should be excited by energetic electrons that are accelerated *via* magnetic reconnection. These nonthermal electrons are then injected into relevant magnetic structures, such as magnetic loops. When an electron beam moves downward along loops, a horseshoe distribution is formed with the increasing magnetic field (Ergun *et al.*, 2000; Bingham *et al.*, 2013). It can also be expected that part of electrons will be reflected as a result of the magnetic mirror effect of magnetic loops. During the process, a ring distribution of electrons (or a loss cone) can form around the reflected point, and then a ring-beam distribution arises when the reflected electrons move upward (Dory, Guest, and Harris, 1965; Trievelpiece, Pechacek, and Kapetanakis, 1968; Wu *et al.*, 2002). Note that nonthermal electrons with the distributions mentioned above are unstable and can efficiently drive ECM (Zhao *et al.*, 2016a,b). In this regard, the inverted V-shape bursts we reported might be associated with electron reflection induced by the magnetic mirroring process in magnetic loops.

5. Conclusions

We have reported a solar radio spike event observed by the newly constructed high-performance metric wavelength solar radio spectrograph at *Chashan Solar Observatory*. Using the high-quality observational data, we found four sets of spike cluster chains with harmonic structures in one solar radio spike event. The harmonic orders vary from the second to the fourth. For the first time, the time delay of the lower harmonics relative to the higher harmonics was determined. The time delay is about 10 ms between the third and the fourth harmonics, and 30–40 ms between the second and the fourth harmonics.

Based on the ECM mechanism, we discussed the cause of the time delays: the difference in group speeds and propagation time in the magnetic loop of various harmonics may cause the delay.

We estimated coronal parameters such as the magnetic field strength in the radio spike source region and the electron density at the escaping sites of the radio waves. The deduced

magnetic strength is 36 G at the radio source. The inferred coronal electron density at the escaping sites of the radio waves is $4.9 \times 10^8 \text{ cm}^{-3}$, $1.1 \times 10^9 \text{ cm}^{-3}$, and $2.0 \times 10^9 \text{ cm}^{-3}$, based on the assumptions that the ECM emission stems from a central density-depleted magnetic loop and the escaping frequency equals to the plasma frequency.

Further observational study with higher temporal resolution (preferably at the millisecond level) and theoretical investigation are required for a more complete understanding, so as to further reveal the diagnostic potential of solar radio spike bursts.

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Conflict of interest The authors declare that they have no conflicts of interest.

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