GENERATION OF ELECTRICITY BY USING BALL SHAPED TRIBOELECTRIC NANOGENERATOR

AUTHOR NAME -

PROF.V.V.GAIKWAD , SUSHANT.S.WAGHMODE , SUJAY.M.GANACHARI , RAJAT.R.PAWAR , ROHIT RAVI

ABSTRACT- The newly developed Hydroelectric Generator (TENG) provide an excellent approach to convert mechanical energy into electricity, Which are mainly based on the coupling between Electrification and electrostatic induction. The TENG has the potential of harvesting many kinds of mechanical energies such as vibration,rotation,wind,human motion and ever water wave energy also, which could be a new paradigm for scavenging large scale energy. It also demonstrate a possible route towards practical application for powering electronic devices. This paper presents a comprehensive review of Generation of electricity by using ball shaped Hydroelectric Generator. The performance of ball shaped TENG for harvesting energy as a sustainable power source are also discussed. Finally,the practical application of Ball shaped TENG for energy harvesting are presented.

KEYWORD - Self-powered system,energy harvesting,contact electrification,ball shaped TENG.

1.INTRODUCTION -

Generally, the electronic devices use batteries as the external power sources. Due to the limited lifetime, the environmental pollution problem, thereplacementofbatteriesandthelargenumberofdevices, and vast scope of distribution, it is thus desirable to replace them by harvesting energy from the ambient environment assustainableself-sufficientpowersourcestomaintainindependent and continuous operations of these electronics. In this regard, energy harvesting techniques have been developedforsupplyingenergytoelectronicdevicesbyconverting ambientenergyintoelectricalenergy.Mechanicalenergy,due toitsabundance,hasbeenoneofthemajorenergysourcesfor energyharvestingsystemsTodate,manymechanisms ofenergyharvestingtechniqueshavebeendevelopedthatare based on various mechanisms including piezoelectriceffect, electrostatic effect, and electromagnetic induction, which havebeenextensivelydevelopedforafewdecades.[REFERENCE - [1.]Simon, Patrice, and Yury Gogotsi. 2008. "Materials for Electrochemical Capacitors". Nature Materials 7 (11): 845-854. doi:10.1038/nmat2297.[2] Wang, Z. L. 2006. "Piezoelectric Nanogenerators Based on Zinc Oxide Nanowire Arrays". Science 312 (5771): 242-246. American]

Mostrecently, a new type of energy harvesting technology named as hydroelectric generator (TENG) has beeninvented asanalternativemethodforscavengingtheambientmechanical energy in the environment to electricity.Accordingtotheexistingreviews on TENG, this paper covers the recent progress in ball shaped TENG asarenewableandsustainablepowersource.Nevertheless, the present works mainly focus on the structure and performance optimization of single devices, while the TENG network still remains to be experimented.In this work, TENG networks based on an optimizedball- shell structured unit are reported. First, we demonstrate a TENG unit using treated silicone rubber as hydroelectric materials, which gives a high output at small agitations.The dynamic behavior and angular dependence under harmonic and impactagitationsarestudiedcomprehensivelytoobtainafull understanding of such kinds of TENG units. Theaggregated performanceofmultipleTENGunitsisalsoinvestigated,and quasi-continuousdirectcurrentcanbeobservedforgroupsof TENG.Basedonthese,acouplingbehaviorforunitslinked with each other in TENG networks is presented. The charge outputforrationallydesignedcoupledunitsisover10timesof that without coupling. [REFERENCE-[3] Momeni, K., G. M. Odegard,and R. S. Yassar. 2010. "Nanocomposite Electrical Generator Based on Piezoelectric Zinc Oxide Nanowires". Journal of Applied Physics 108 (11): 114303. AIP Publishing. doi:10.1063/1.3517095.

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2.STRUCTURE AND WORKING PRINCIPLE -

Aphotographofasplit ball-shell structured TENG unit is shown in Figure 1a,and Figure 1eillustratesitsdetailedstructure.The TENG unit consists of one ball and two semi sphericalshells with metal electrodes and dielectric layers on their inner surfaces.Figure 1c anddshowsagroupoffabricatedballsand shells.Here,siliconerubberwasusedtopreparetheball and thedielectriclayer,whereitssoftnesswouldenhancethereal contact area and contribute to the durability of the device.

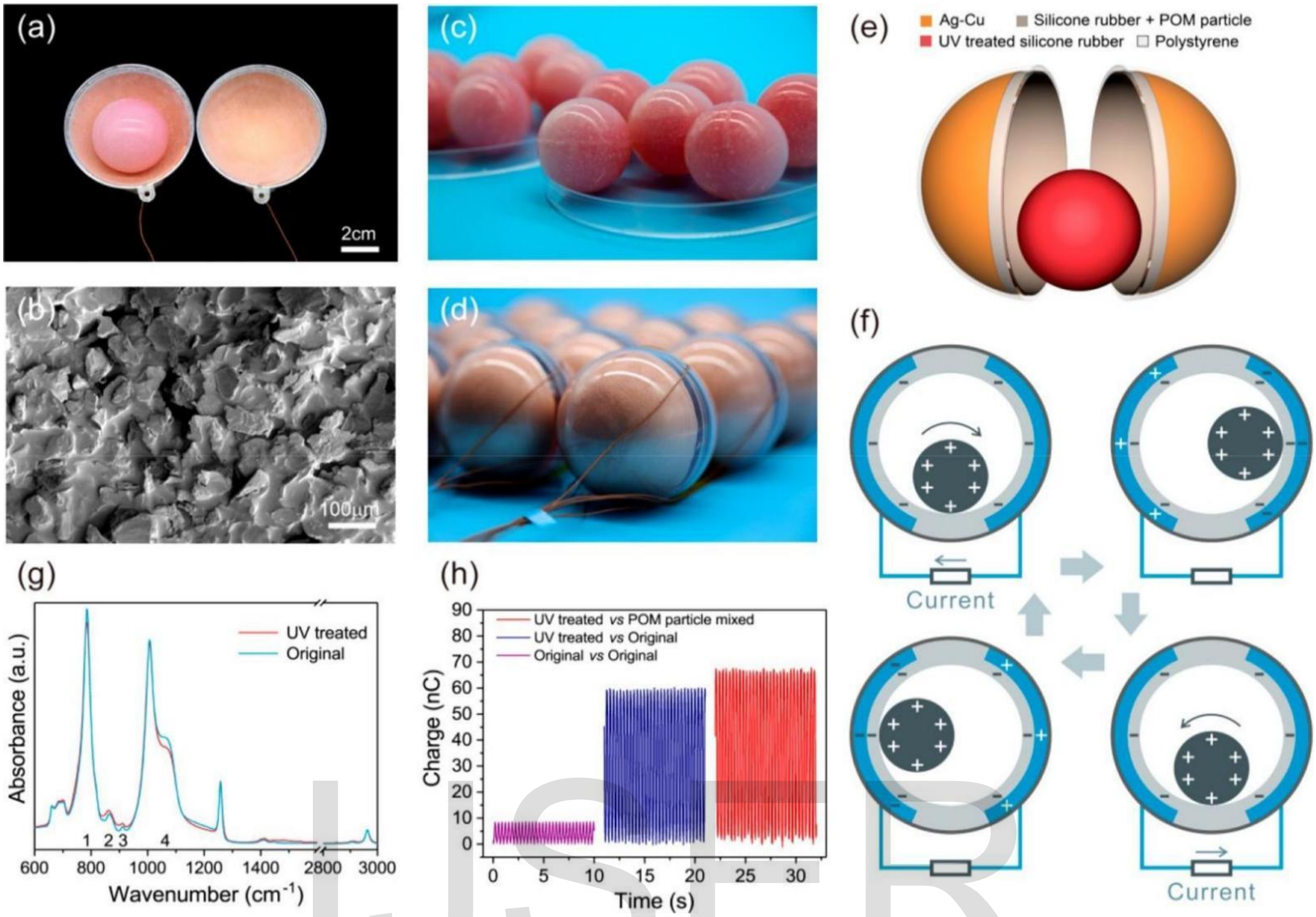

Figure1.StructureandworkingprincipleoftheTENGunit.

(a,c,d)Photographsofasplitball-shellstructuredTENGunit,siliconerubber balls,andoutershells.(b)SEMimageofsiliconerubbermixedwithPOMparticles.(e)SchematicstructureoftheTENGunit.(f)Working principleoftheTENGunit.(g)FTIRspectraoftheUVtreatedandtheoriginalballs.(h)Electrification performance for different pair of the ball and the shell under the same harmonic agitation.

Ultraviolet(UV)treatmentwasappliedtotheball,whichhasa modification effect to the surface as shown in Figure 1gthe Fouriertransforminfrared(FTIR)spectraoftheoriginaland the UV treated silicone rubber indicate decreased Tofurther enhancethecontact,formaldehyde(POM) particles were mixed into the dielectric layer, fabricating micro structure on the surface, as shown in Figure 1b (bare silicone rubber surface is shown in Figure S1for comparison).TheUVtreatmentandthemicro structuresalso makethefacelesssticky,enablingsmoothrolloftheball onthedielectriclayerwithrelativelowdampingforce,whichis crucialfortheperformanceof theTENGunitagitatedbyslow water waves. The electrodes were fabricated by painting commercial Ag-Cu conductive paint on the inner surface of theshell.The operation mechanism of the TENG unit ismainly based on the conjugation of triboeelectric and electrostatic induction.electrodeson the shell through an external circuit, generating alternate current in the circuit. To stimulate the roll of the ball in the shell,variousmechanicalagitationscanbeadopted,likerotate orlinearlyshaketheshell.Suchmechanismofthedevicecanbe classified into the freestanding triboelectric layer mode,where the ball acts as the freestandinglayer [REFERENCE-.[5]von Buren, T., Mitcheson, P., Green, T., Yeatman, E., Holmes, A. and Troster, G. (2006). Optimization of inertial micropower Generators for human walking motion. IEEE Sensors Journal, 6(1), pp.28-38.[6] Gu, L., Cui, N., Cheng, L., Xu, Q., Bai, S., Yuan, M., Wu, W., Liu, J., Zhao, Y., Ma, F., Qin, Y. and Wang, Z. (2012). Flexible Fiber Nanogenerator with 209 V Output Voltage Directly Powers a Light-Emitting Diode. Nano Letters, 13(1),[7] pp.91-94.Pelrine, R., Kornbluh, R., Eckerle, J., Jeuck, P., Oh, S., Pei, Q. and Stanford, S. (2001). Dielectric elastomers: generator mode fundamentals and applications. Smart Structures and Materials 2001: Electroactive Polymer Actuators and Devices.]

3.CHARACTERIZATION OF SINGLE TENG UNIT -

To comprehensively understand the behavior of the TENG under externalmechanicalexcitation,asingleunitwasclampedina chuckingonalinearmotorthatcanimposeharmonic and impactagitationstotheunitinatranslationmode,asshown inFigure2a.

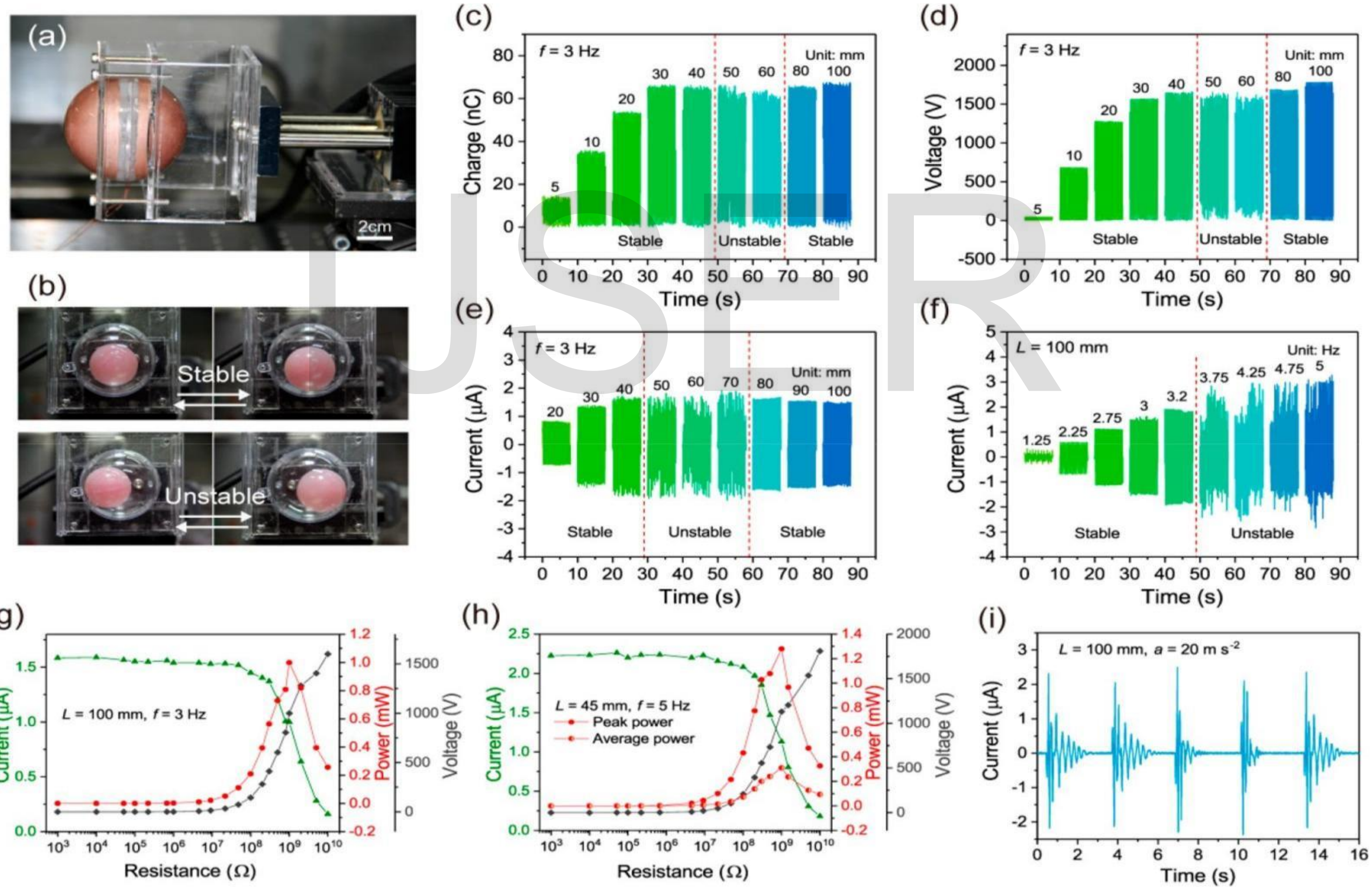

Figure2.ElectricalcharacterizationofasingleTENGunitbyamotorinair.

a)ExperimentsetupforsingleTENGunittests.(b)Thestable andunstablemotionoftheballinashellwithoutelectrodesanddielectriclayers.(c & e)Dependenceoftransferredcharges,opencircuit voltage,andshortcircuitcurrentonthedisplacementamplitudeofharmonicagitations.(f)Dependenceofshortcircuitcurrentonthe frequencyofharmonicagitations.(g &h)DependenceoftheoutputpoweroftheTENGuniton resistance loadsfordifferent harmonic agitations. (i) Short circuit current of the TENG unit for impact agitations .

As shownin Figure2c,foranagitationof3Hz,theshortcircuit transferredcharges Q $_{SC}$increaserapidlywithinitialriseofthe displacement amplitude, from 14 nC at 5 mm to 66 nC at30 mm,thensaturatewithfurtherincreaseoftheamplitude.The opencircuitvoltage $V_{OC}$and theshortcircuitcurrent I_{SC}show similar behavior, which can reach 1780v. respectively, in the stable region (Figure 2d and e).Such behaviorindicatesthatthedevicecanpresenthighperformance undersubtleagitations,whichisidealforwaterwaveenergy harvesting.Itcanbeobservedthatthere existsaregionaround 50mmto60mm,wheretheoutputwaveformischaotic.This can be attributed to the unstable motion of the ball as illustratedinFigure2bandVideosS1andS2intheSupporting Information. Different from a stable motion where the ball simplyrollsalongtheagitationdirection,theballinanunstable motion state would roll in a chaotic way, sometimes perpendicular to the agitation direction. The phenomenon shouldoriginatefromthenonlineardynamicnatureoftheball systemthatcouldshowcomplexbehaviorundersimple excitation.Insuchunstablemotionstate,thedevicewouldnot haveastrongdependenceonthedirectionofthewaterwave, and whatever the agitation direction is, the ball could have movementalongthedirectionbetweenthetwoelectrodesthat cangenerateelectricityeffectively.Thedependenceoftheshort circuitcurrentonthefrequencywasalsoinvestigated,asshown in Figure 2f. The current increases monotonically with the frequencyandentersanunstableregionafter3.2HZ,Themaximu mpeakpowerP_{peak}reaches1 mWand1.28mWforagitationsof3and5Hz,respectively,with

EQUATION,- $$\mathbf{Pave} = \frac{\int_{T0}^{T0+T} I^2 R dt}{T}$$,

Theballwilloscillatetooutputabout10pulsesofcurrentaftersingl eimpacts.Thisshowsthatthedevicecanstorethemechanicalener gyandcontinuouslytranslateitintoelectricitythroughinternalvibra tionsafterward.Whileinoperation,thesoftsurfaceoftheinnerball prohibitstheballfromviolentlycollidingwiththeshell.Thus,thed eviceisexpectedtohaveexcellentdurability.ATENGunit testedfor in our experiments, and an 1 h continuous test is shown in Figure 3 in the Supporting Information.severaldayscanstillhaveverystableoutputwithout anydecay dependence of the output performance in a stable motion. First, as shown in Figure 3a and d, we define a middle plane that lies in the middle between the two semispherical electrodes, and two orientation angles, that is, yaw there will be electricaloutputtheoreticallyonlywhenthemovementofthe ballhaveanonzeroprojectioninthedirectionperpendicularto themiddleplaneaccordingtotheproposedworkingprinciple in -Figure1f. Zhang, C.; Tang, W.; Han, C. B.; Fan, F. R.; Wang, Z. L. Theoretical comparison, equivalent transformation, and conjunction operations of electromagnetic induction generator and triboelectric nanogenerator for harvesting mechanical energy. Adv. Mater. 2014, 26, 3580–3591

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4.CHARAACTERIZATION OF RIGID NETWORK -

in the experiments,we first increased the yaw angle 0^0 to 90^0 and measured the transferred charges,as show in fig 3b. the transferred charges decrease slowly with larger angles. for a worst situation of 90,where the deviceshould havenooutputtheoreticallybecausetheballwouldrollalong themiddleplane,thereisstillanoutputofabout25nC.This shouldbeattributedtosmallasymmetriesinthemotionofthe balltothemiddleplaneandtheget a reliable comparison of the accumulativeoutputcharges,whichshowssimilartrend,and the charging rate is about 77%and 66 and 35 for 90, as compared output charges which show similar trend,upperelectrodeinasinglerollcycle,producingtwopulses ofoutput. Forasmaller application ofwaterwaveenergyscavenging,TENGnetworksarerequiredfor large-scale energy harvesting.[REFERENCE-[11]Wang, Z. L. Triboelectric nanogenerators as new energy technology for selfpowered systems and as active mechanical and chemical sensors. ACS Nano 2013, 7, 9533–9557 [12]Park, Kwi-Il, Sheng Xu, Ying Liu, Geon-Tae Hwang, Suk-Joong L. Kang, Zhong Lin Wang, and Keon Jae Lee. 2010. "Piezoelectric Batio3thin Film Nanogenerator On Plastic Substrates". Nano Letters 10 (12): 4939-4943. doi:10.1021/nl102959k.[13]Bhushan, Bharat (15 March 2009). "Biomimetics: lessons from nature-an overview". Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences. 367 (1893): 1445–1486.Williams, Hugo R.; Trask, Richard S.; Weaver, Paul M.; Bond, Ian P. (2008). "Minimum mass vascular networks in multifunctional materials". Journal of the Royal Society Interface. 5 (18): 55–65. doi:10.1098/rsif.2007.1022.]

TheelectricalconnectionofthearrayisshowninFigure4b.Considering itdoesnotnecessarilyhavethesamephase,theoutputofeachunitis react first,andallofthemareconnectedinparallel.The array was tested with harmonic agitationsandimpactagitations,respectively.

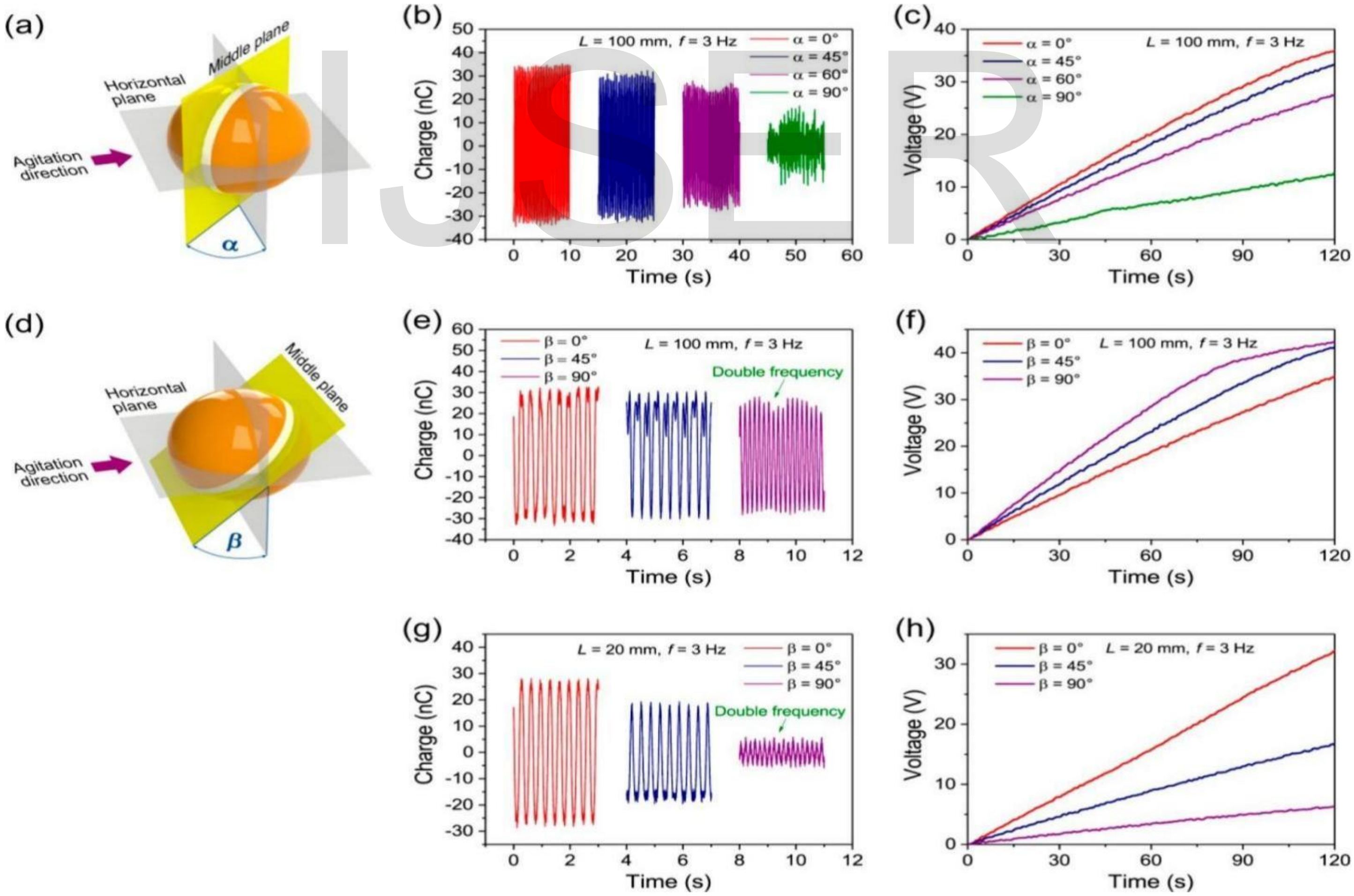

Figure 3.Electrical characterization of the 4 x 4 TENG array in air

Photograph of the 4x4 TENG array.(b)Schematic diagram of the rectification circuit for array.(c & g)output

oftheTENGarrayforharmonicagitationswithL=40mmandf=3Hz:(c)istransferred chargesforeachTENGunitinthearray,(e)showsrectifiedshortcircuitcurrentwithdifferentamountsofTENGunits,and(d,f,g)show chargeoutput,shortcircuitcurrent,andopencircuitvoltageofthearraywithrectification.TheTENGunitsarenumberedas notedin(c)and (e) .(h,i)Rectifiedshortcircuitcurrentofthearrayunderimpactagitationsofdifferentaccelerationsandfrequencies.(j,k)Dependenceof theoutputpowerofthearrayonresistance loadsforharmonicagitationsandimpactagitations,respectively.(l)Chargingperformanceofthe array for different capacitors with harmonicagitations.

We firsttestedthetransferredchargesofeachunitwithoutrectifierun derharmonicagitations,asshowninFigure4c.Theperformanceof eachunitshowsgood uniformity,withanaveragevalueof66.9nC anda maximumof 1.72.6 nC, which is about 3 times as high as the highest value reported.. The value is almost precisely the add-up of the output from each single unit in Figure 4c multiplying by factor 2 due to the rectification effect.the short circuit current shows a liner dependence on the amount of unit,reaching 18.1 for 16 parallel connected units,as shown in fig 4 e and f.this resonance considering that the current is related to the rate of change transfer where equation is ,

$\mathbf{I_{sc,n}} = \frac{dQ_{sc,n}}{dt}$,Iscn and Qscnrepresent short circuit current and transferredchargesofnunits,respectively.Inthepresentarray, therigidconnectionmakestheballineachunitrollinroughly thesamepace,thuswiththelinearincreaseof $Q_{SC,n}$byn, $I_{SC,n}$willalsoincreaselinearly.Themeasuredopencircuitvoltage of the array V_{OC} is about 1020 V (Figure 4g), which is lower thanthevoltageofasingleunitmentionedabove.[REFERENCE-

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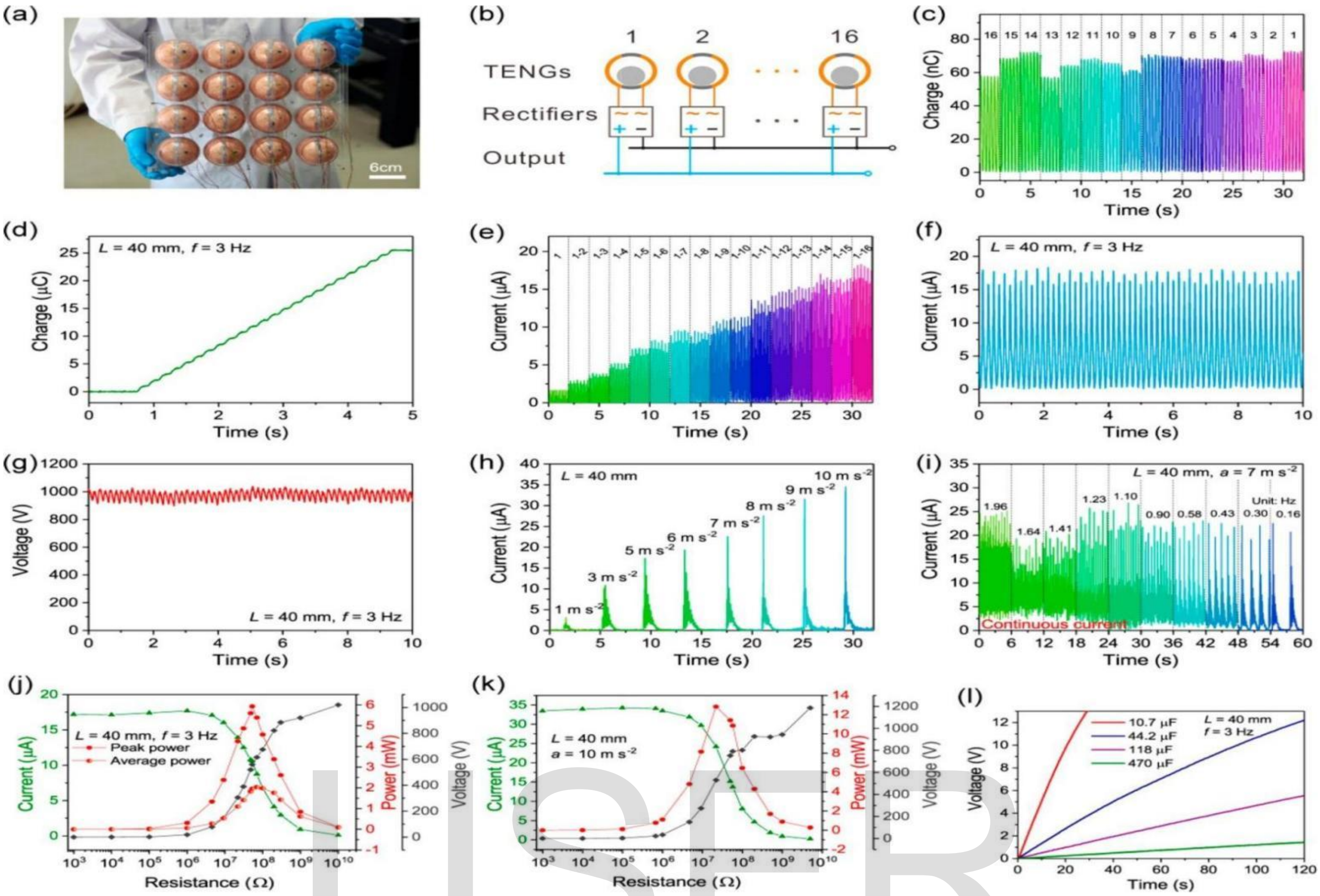

Figure 4 .Electrical characterization of the 4x4 TENG array in air

A.photograph of the 4x4 TENG array.(b)schematic diagram of the rectification circuit for the array.(c-g)o/p Of the TENG array for the harmonic agitation with L=40mm,and f=3Hz (c)is transferred charges for the each TENG unit in the array,(e)shows rectification short circuit current with different amounts of TENG units,and(d,g,f)show charges output short circuit,and open circuit voltage of the array with rectification.the TENG units are numbered as noted in (c)and(e). (h,i)rectification short circuit current of the array under impact agitation of different acceleration and frequencies.(j,k)Dependenceof theoutputpowerofthearrayonresistiveloadsforharmonicagitationsandimpactagitations,respectively.(l)Chargingperformanceofthe array for different capacitors with harmonicagitations.

Thechip usedherehasamaximumblockingvoltageofabout1000 V, thus it cannot reliably hold a higher voltage between the positiveandthenegativepinsduetoarapidincreasingreverse currentininternaldiodeswithhigher voltage. Because the open circuit state with the high voltage is not used for application here,we still use this rectifier in the research for its low cost and commercial availability.The performance of the array under impact agitations is showninFigure4handi.Whiletheaccelerationofagitationsa increases,thepeakshortcircuitcurrentalsorisesalmost linearly.and achieves 34.5 with an acceleration of 10 ms. for each current phase,there is a long tail lasting about 1.8s,wherethe current gradually decays to zero (Figure 4h). Due to such currenttails,withshorterimpactintervals,thecurrentpulses corresponding to successive impacts would have influence with eachotherand finallypresenta continuous resistive loads was measured under harmonic and impact agitation respectively.for harmonic agiations the measured data show a maximum peak power of 5.93mw.at 52.88 (figure 4j).and the maximum peak power of bout 2.06 wm^3.andextendsinto5mindepthofwater,witheachunit spacedabout7.5cm,a maximumaveragepowerof1.51MWis expected to bedelivered Forimpactagitations,asshowninFigure4k,themeasured data methods.

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show a maximum peak power of 12.3.mw. electronics,likethermometers,anemometers,etc. In the study wave experiment were carried out to test single TENG unit and 4 x 4 TENG arrays with different network connection

5.COUPLED TENGNETWORKS IN WATER -

TheTENGnetwork isproposedtoharvestwaterwaveenergyinalargearea.However, it is still not clear how the network should be organizedtoreceivethemaximumoutputpower,andwhatis thefunctionofthenetworkingbesidesharvestingenergyfrom distributed local sites. In this section, we investigate TENG arraysinrealwatercircumstancesandshowacouplingbehavior between TENG units by networking, which acts as a crucial role for TENG an work effectively on the water wave.The setup of the wave tank in the Supporting Information. First, as illustratedinFigure5a,twosortsofTENGunitsweretested, referred to as the free-unit and the linked-unit.theTENGisconnectedtoa fixedpoleabovethe watersurfacebyapoly carbonate(PC)stripof1cmwidthand 0.3 cm thickness, mimicking units with certain mechanical coupling to a network.Thetransferredchargesofsuchunitsareshownin Figure 5b.for the TENG unit,obvious drifts of the baseline of change output can be observed,which reflect that the inner ball rolls to certain sites without completely rolling back due to orientation changes of the whole unit without unit.without effective constraints of the linkage,the orientation of the unit would vary arbitrarily,sometimes in a dead state where there is almost no output (Video S3 in the Supporting Information).

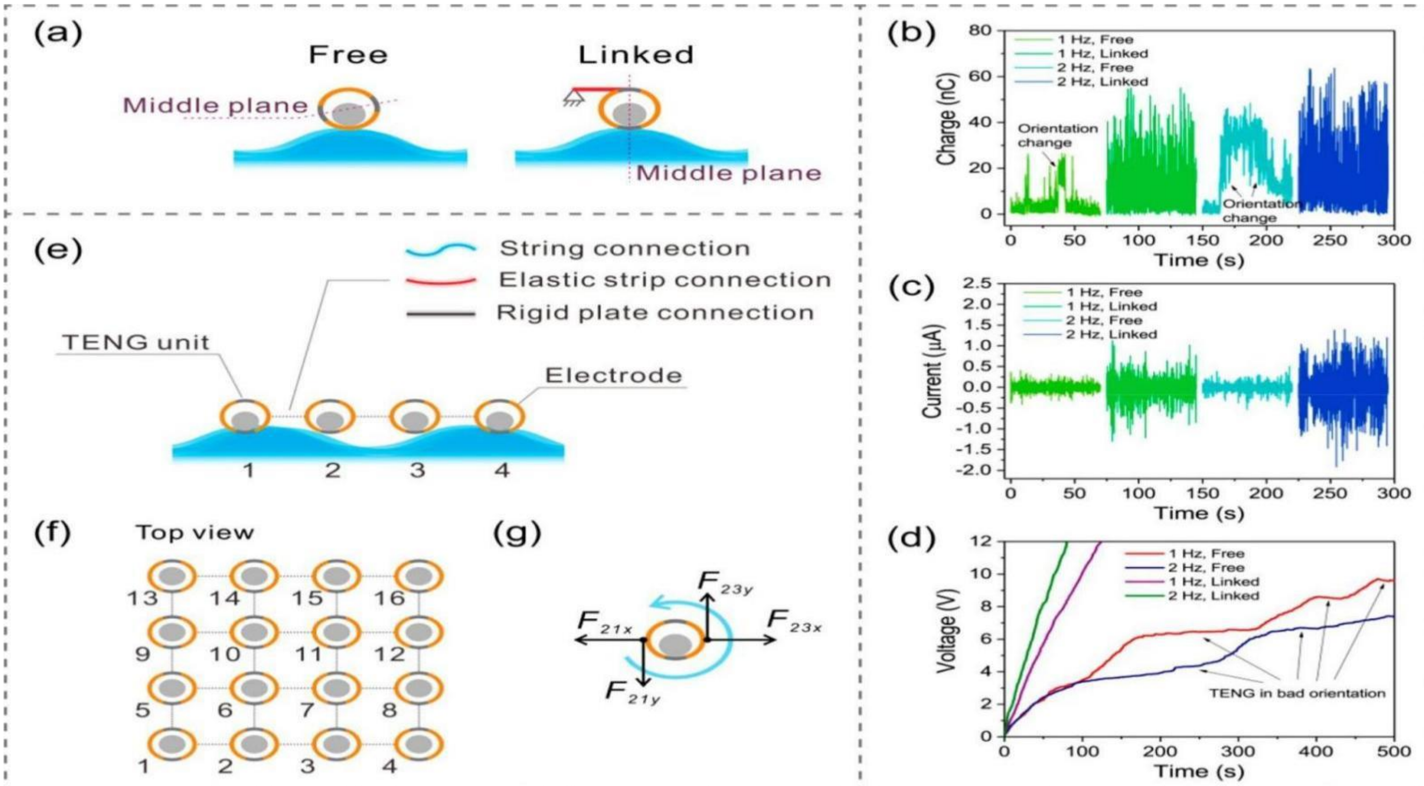

Figure 5. Schematic diagram and output comparison of mechanical connections for TENG units in water.

(a)Schematicdiagramofthe experimentsetupforasingleTENGunitinwater.(b,c)TransferredchargesandshortcircuitcurrentfortheTENGunitindifferentstates.(d)ChargingperformancetoacapacitorofI.07μFfortheTENGunitindifferentstates.(e,f)Schematicdiagramofnetworkconnecting strategies. (g) Force analysis for a TENG unit in thenetwork.

Even in good orientations, the transferred charges can only reach about30 nCfor2Hzwaterwaves.Forthelinked-unit,theperformance improves,withtransferredchargesof63nCand55 nCin2and1Hzwaterwaves,respectively,andthedriftofthe baselineissuppressed.Thecomparisonshowsthecrucialroles played by the linkage that couples TENG units for proper operation in water. Two effects can be concluded: First, the constraint effect of the linkage helps the unit to maintain an optimum orientation as discussed above; and second, the linkage would transfer force and energy between units and imposeatorquetotheunitaccompaniedbythepushofwater waves, which drives the unit to rotate and to be excited effectivelybyslowwatermotion.Thesecondeffectcanexplain why even both in good orientations, the output improves substantially for the unit in the linked state versus that inthe freestate.TheshortcircuitcurrentshowninFigure5cfurther confirms theroleplayedbythelinkage.Wealsotestedcharging performanceoftheunits to a capacitor of 1.07,to show the long term charge output and suppress short term randomness (figure 5d). Charging curves for the free-unit show obvious plateaus where the voltage of the capacitor hardly has any increase for a long time. For the linked-unit, the charging is much faster, improving to about 11.6 times for 2 Hz water waves, to charge the capacitor to 7.5 V.Theabovedataindicatethattheeffectsofproperas dispersed units covering large areas without linkage. Thus, mechanicalconnectionsbetweenunitsintheTENGnetworks to effectively couple each unit play crucial roles. In the networks, each unit is mechanically linked to other units, so thatthecorrelativemechanicalmovementbycouplingamong themgivesahighoutput.[REFERENCE -[23].Su, Yuanjie, Xiaonan Wen, Guang Zhu, Jin Yang, Jun Chen, Peng Bai, Zhiming Wu, Yadong Jiang, and Zhong Lin Wang. 2014. "Hybrid Triboelectric Nanogenerator For Harvesting Water Wave Energy And As A Self-Powered Distress Signal Emitter". Nano Energy 9: 186-195. doi:10.1016/j.nanoen.2014.07.006.[24.]Lin, Zong-Hong, Gang Cheng, Wenzhuo Wu, Ken C. Pradel, and Zhong Lin Wang. 2014. "Dual-Mode Triboelectric Nanogenerator For Harvesting Water Energy And As A Self-Powered Ethanol Nanosensor". ACS Nano 8 (6): 6440-6448. doi:10.1021/nn501983s.]

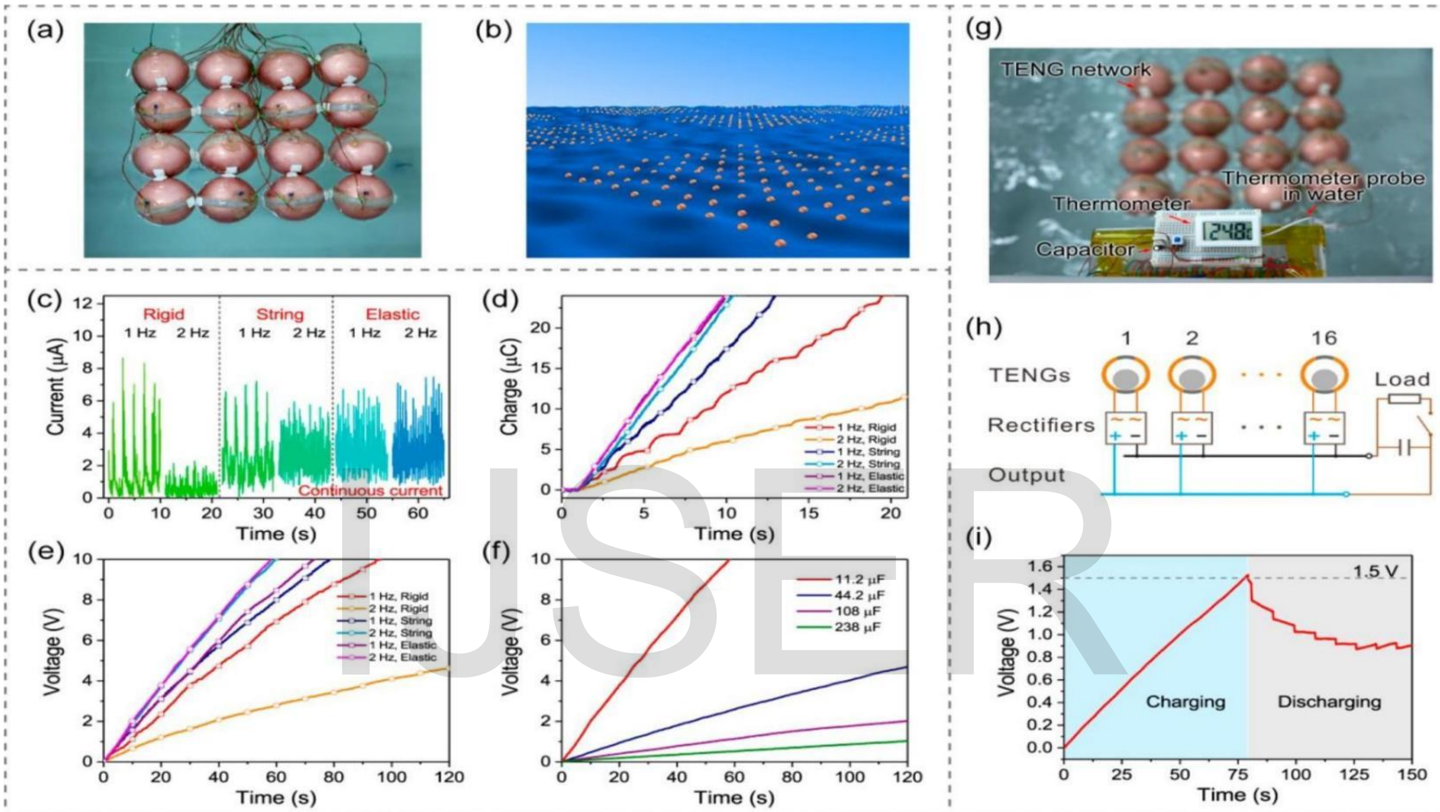

Figure6.ComparisonoftheTENGnetworkswiththreedifferenttypesofconnectingstrategiesinwater Photographofthestring connectedTENGnetwork.(b)Imaginarypictureoffuturelarge-scaleTENGnetworksfor harvesting water wave blue energy.(c,d)rectified short circuit current and transferred charges of the three different types of TENG network.(e)charging performance of the three types of network to a capacitor of 11.2. (f)Chargingperformanceoftheelasticstripconnectednetworktodifferentcapacitorsunderwaterwaves of2Hz.(g)Photographofthestringconnectednetworktopowerathermometer.

Tofurtherillustratetheideaandtest different connections, networks with three types ofconnections were proposed, that is, rigid plate connection which will not deform,elasticstripconnectionthatcandeformtosomeextent, and string connecting that can freely deform without extension,as shown in fig5e,a capacitor of 11.2 was charged withthesenetworks,asshowninFigure 6e.Thetwo flexibleconnectionshavesimilarperformancefor the same water wave frequency, with the cases at 2 Hz a bit higherthanat1Hz.Therigidconnectionshowsweakeroutput at 1 Hz and the worst result at 2 Hz. The above experiments indicate that flexible connections are better networking strategiesthantherigidonewhichimposestoomuchinternal constraints betweenunits. Theelectricalcircuitis shown in figure 6h. asshowninFigure6gandVideoS6in the Supporting Information. The initial charging process took only about 78 s at 2 Hz using the string connected network(Figure6i).Amoreprofoundideaistoharvestwater waveenergyfromlargeareaswithscaledupTENGnetworks, thatis,blueenergy,asshowninFigure6b.Withcoupling betweenunits,theTENGnetworkisprovedtobeaneffective way to harvest water wave energy. The aggregated powerof units in large areas can be huge. Such electricity can be transferred to the grid on land or to small islands through submarine cables, providing an inexhaustible clean energy source forhumansconnected network,everytwoneighboringTENGunitsinthe array were bunched with strings by a distance of about 1cm[REFERENCE -Liang, Qijie, Xiaoqin Yan, Yousong Gu, Kui Zhang, Mengyuan Liang, Shengnan Lu, Xin Zheng, and Yue Zhang. 2015. "Highly Transparent Triboelectric Nanogenerator For Harvesting Water-Related Energy Reinforced By Antireflection Coating". Scientific Reports 5 (1). doi:10.1038/srep09080.

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6.EXPERIMENTAL SECTION -

6.1.FABRICATION OF TENG UNIT -

Fortheinner ball,thebaseand thecuringagentofthesiliconerubber(PS6605)weremixeduniformly by volume ratio 1:1 and then poured into a ball-shaped mold with innerdiameterof4cm.Ahollowplasticballof3cmwasplacedin 1:1 and then poured into a ball-shaped mold with inner diameter of 4cm. A hollow plastic ball of 3cm was placed in the center of the mold to be wrapped up by the silicon rubber.after curing for 1h at the temperature of 60 ^{0}c,a hollowsiliconerubber ballwasprepared.TheballwasthenUVtreatedfor10minusingan UVcleaner(BZS250GF-TC).Fortheoutershell,Ag-Cuconductiv e paint(CHANGYAUN6330)waspaintedontheinnersurfaceof the shell which has a diameter 7 cm and baked at the temperature 60^{0}c for 0.5 h to form a tough layer of metal electrode. Thesiliconerubber (PS6605) was then smeared over the electrode with POM particles sprayedonand cured for 1 h at the temperature of 60^{0}c.

6.2.FABRICATION OF THE NETWORK -

For the rigid plate connected network,the16TENGunitswereplacedbetweentwoacrylicplat es whichhave16 round holes with a diameter of 6.3cm in 4x4arrey,and the TENG units were seated firmly in the holes.for the elastic stripconnectednetwork,plasticstripswithawidthof1cmwereg lued on every two neighboring TENG units to form a 4x4 arranged TENG array,according to the topology shown in figure 5f. for the connected network,every two neighboring TENG array,according to the topology shown fig 5f. for the string

6.3.ELECTRICAL CHARACTERIZATION -

The open circuit voltage was measured by an electrostatic voltmeter (Trek 344). The transferred chargesandthecurrentweremeasuredbyan electrometer (Keithley 6514).

7.ASSOCIATED CONTENT -

<u>SupportingInformation</u>

(REFR - TheSupportingInformationisavailableonthe ACS Publications website at DOI:10.1021/acsnano.7b08674.)

SEM images of bare silicone rubber surface; typical displacement curves for agitation movement of the motor transferredchargesoftheTENGunitunderlong-timeoperation;setupforwavetankexperiments(PDF)

Video S1: Stable motion of the ball in a shell without electrodes and dielectric layers(AVI)

VideoS2:Unstablemotionoftheballinashellwithout electrodes and dielectric layers(AVI)

Video S3: Free TENG unit under water waves of 2Hz AVI)

Video S4: Rigid network under water waves of 2 Hz (AVI)

VideoS5:Stringconnectednetworkunderwaterwaves of 2 Hz(AVI)

Video S6: Powering a thermometer by the string connected network (AVI)

8.CONCLUSION -

Insummary,coupledTENGnetworksbasedonoptimizedTENG unitsforwaterwaveenergyharvestingarereported.A rationaldesignonthecouplingamongunitsgreatlyenhances theoperatingefficiencyofthenetwork.Thechargeoutputof the coupled units is over 10 times of that without coupling. TENG networks of three different connection methods were fabricatedandcharacterized,with flexibleconnectionsperformingmuchbetterthantherigidoneforextrainternaldegreesof freedom.TheunitoftheTENGnetworkadoptsatypicalball- shell structure with optimized designs that have high response to small agitations. The dynamic behavior and angulardependenceunderharmonicandimpactagitationsare studiedcomprehensivelytoobtainafullunderstandingofsuch kindofTENGunits.Theaggregatedperformanceofmultiple TENG is also investigated, and a quasi-continuous direct current can be observed for groups of TENG. The report demonstrates that the coupled TENG network is aneffective way to harvest water wave energy, toward the blue energy dream.

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