Propagation and control of nanoscale magnetic-droplet solitons

M. A. H $f^{-1,*}$ $f^{-1,*}$ $f^{-1,*}$ M. S and $f^{-1,+}$ and T . J. Silva $2, \frac{1}{4}$

¹*Department of Mathematics, North Carolina State University, Raleigh, North Carolina 27695, USA* ²*National Institute of Standards and Technology, Boulder, Colorado 80305, USA* $(R_{c} + 21 J_{c} - 2012;_{e} + 1 + 26 J_{c} - 2012)$

 T_{max} propagation and controlled manipulation of strongly non-linear, two-dimensional solitonic states in a state t , and anisotropic ferromagnet are theoretically proposed that spin-polarized $c_{\rm c}$ rents in a nocontact device could be used to nucleate a stationary dissipative droplet soliton. Here, and external and ext magnetic field is introduced to accelerate and control the propagation in a lossy medium. Soliton in a lossy medium \mathcal{S} perturbation theory corroborated by two-dimensional micromagnetic simulations predicts several intriguing physical effects, including the acceleration of a station by a magnetic field gradient, the station by a station by a magnetic field gradient, the station by a magnetic field gradient \mathbf{r}_i of a stationary ss6281.8lossyst2 .70*.*−i

 $N_{\alpha}^{\mathfrak{g}}$ and $\beta_{\alpha}^{\mathfrak{g}}$, $\beta_{\alpha}^{\mathfrak{g}}$ for $\beta_{\alpha}^{\mathfrak{g}}$, $\beta_{\alpha}^{\$ $j \in \{0, 1\}$ abling physical effect is spin to $\frac{2}{\pi}$ which imparts and $\frac{2}{\pi}$ \mathbb{R}^m spin-polarized current to a magnetic to a \mathbf{u}_t for \mathbf{f}_t in *confined* nanopillar structures[3](#page-5-0) and nanocontacts abutting **c** extended **f** reasonably described by single-domain \mathbb{R}^n the domain \mathbb{R}^n with the domain \mathbb{R}^n notable exception of gyrotropic vortex \mathbf{g}^{\prime} , \mathbf{g}^{\prime} and \mathbf{g}^{\prime} and \mathbf{g}^{\prime} $n_{\rm e}$ nable the enable the excitation of $r_{\rm e}$ and $r_{\rm e}$ and lo- ϵ calized, coherently precessing, non-linear wave states. 8 T 8 T is $\mathcal{S}(\mathcal{A})$. Analysis of systems in nanocontact systems has pre- α dominantly between limited to either the weakly non-linear regime α at the threshold \mathbf{t} or complex micromagnetic simulations. The complex micromagnetic simulations. S,11 W_{α} recently proposed that a spin torque driven nanocontact \mathcal{G}_{α} spin to \mathcal{G}_{α} $c_{\rm eff}$ could act as a soliton creator in a unitary \mathfrak{g} in a unitary \mathfrak{g} ferromagnetic with \mathfrak{g} $\frac{1}{2}$ sufficiently strong perpendicular anistropy. 12 The resultant anistropy. \mathcal{S} is the strongly non-linear, coherently precession state was termed was termed was termed was termed was term a distinguished soliton, the local driven/ \mathcal{B} driven/uniformly $\alpha = \alpha$ damps of the two-dimensional, non-dimensional, non-dimensional droplet α s stiton. \mathbf{N} and s is the first observation of the dissipation of the dissipatio α' and α' is been very recently recently reported. The β numerical computations suggested that the conservative $\mathfrak{g}_\mathbb{Z}$ at $\mathfrak{g}_\mathbb{Z}$ at \mathbb{Z} $-$ UJ-0-1.154, tact as stable, particle in the particle dipoles that p is precessed that p $er_{\mathbb{Z}}$ \mathcal{L} and \mathcal{L} applications. $f_H v^*$. Fig. model equations and then proceed with the finite-dimensional reduction via soliton perturbation theory. The reduced system syste $e^{i\theta}$ enables a thorough analysis of drople[t dy](#page-5-0)namics under the dynamics under the dyn influence of damping and a spation of damping and a spation of \mathcal{L} \mathfrak{g} undertaken in the next section. Two control mechanisms, \mathfrak{g} $\mathbf f$ eedback control of a stationary droplettery droplettery droplettery droplettery and $\mathbf f$ \mathcal{L} and \mathcal{L} and \mathcal{L} are the propagating dropletting droplettin $\sum_{i=1}^n \alpha_i \alpha_i \alpha_i$. We conclude α_i with some discussion and future with some discussion and future $\frac{c}{\tau}$ **II. MODEL** $T_{\rm eff}$ model of magnetization dynamics we consider \mathbf{f} L_{ν} \sim_L -Lifshitz equations for \sim $L_{\text{a}}\Omega P = \frac{Z}{2}m + (h_0 + m_z)Z,$ (1) $_{eff}$ – *m* × (*m* × *h*_m) $\frac{\partial \Phi}{\partial x} \frac{\partial \Phi}{\partial y} = \frac{\partial \Phi}{\partial y} \frac{\partial \Phi}{\partial x} + \frac{\partial \Phi}{\partial y} \frac{\partial \Phi}{\partial y} + \frac{\partial \Phi}{\partial y} \frac$ 0 is the damping parameter $\frac{1}{2}$ is the damping parameter $\frac{1}{2}$ ferromagnet. The effective parameters \mathcal{L} r inc $^2m, \mathcal{L}$ incorporates \mathcal{L} and \mathcal{L} 1098-0121/2012/85(21)/214433(7) 214433-1 [°] 2012 A \downarrow P \downarrow P \downarrow S \downarrow

 $h_0(x,t)z$ **b** $f : b$ **p c p c c** *d* **f c** *d* **f** $\begin{CD} \mathcal{A} & \mathbf{0} \in \mathbb{R}^n, \mathcal{A} & \mathbf{0} \in \mathbb{R}^n, \mathcal{A} & \mathcal{A} & \mathcal{B} & \mathcal{B} & \mathcal{C} & \mathcal{B}$ $\begin{array}{c} \mathfrak{g} + \begin{array}{c} \mathfrak{g} + \mathfrak{g$ $s_{\rm eff}$ such sufficient to overcome the local demagnetizing field solution \mathcal{L} that *H > M* . Time, space, and fields are normalized by scaled ℓ **versions of the Larmor frequency i** $\mu_0 M (Q-1), \ldots, \mu_L$ length*L*ex*/ Q* − 1, and saturation magnetization *M* (*Q* − 1), respectively, where $Q = H/M > 1$. We note that for the form s solitons studied here, the magnetostatic field is approximately is approximately is approximately is approximately in f local for films with thickness much smaller than *L*ex*/ Q* − 1 (see Discussion in Ref. [17\)](#page-5-0). For Co/Ni multilayer anisotropic $f = \frac{1}{2}$ the temporal experiments used in recent experiments, the temporal experiments, the temporal experiments, $f = \frac{1}{2}$ \mathbb{R} scale and length scale are approximately 27 ps and 17 nm, \mathbb{R} $P_1, P_2, P_3, P_4, P_5, P_6, P_7, P_7, P_8, P_9, P_{10}$ *M* 650 **A**^{\prime}. $R[\mathbf{f}, \mathbf{b}] = \mathbf{c} \mathbf{b}$, $\mathbf{c} \mathbf{b}$ and \mathbf{c} are parameter values. In which follows, we assume that a localized excitation of $\mathcal{F}_\mathcal{A}$ of large and the large amplitude by a spin torque by a spin torque by a spin torque by a spin torque \mathcal{L} n_a or n_a or n_a or some other means. The rest of this work \mathbf{r}_a is concerned with the manipulation of this structure in a lossy $\mathcal{L}_\mathcal{F}$ $m_{\rm r}$ is the set of an external field. $W \circledast h_0 = = 0, E_0$, [\(1\)](#page-0-0) and the conservation of the conservat $\sum_{i=1}^{n}$, momentum, and energy, and $\sum_{i=1}^{n}$

respectively, where all integrals are taken over the plane $\mathcal{G}(\vec{r})=\mathcal{G}(\vec{r})$ and and and angles of the polar and angles of the theorem and angles of the theorem and angles of the $\mathcal{G}(\vec{r})$ magnetization, respectively. Minimizing the energy subset of energy subsets the energy subject to energy subject to for and N and P parameter $\sqrt{\nabla_{\mathbf{v}}}$ to a two-parameter family of localized, precessing, stable traveling waves called propagating \mathbf{p} that \mathbf{p} is a set of \mathbf{p} solitons parametrized by their velocity *V* and frequency in the comoving frame . 17 17 17 There is a bijective map from $(\mathcal{N}, \mathcal{P})$ $t_{\text{max}} = \mathbf{I}_{\text{max}}$ parameters (*w,V*). Droplet localization \mathbf{I}_{max} $t_{\rm eff}$ the velocity and frequency of the propagation of the propagation droplet lies β of a spin wave band, wave band, enforcing the restriction \mathbb{R}^3

$$
+ |V|^2/4 < 1, \quad V = 0, \quad 0 < 1, \quad V = 0. \tag{2}
$$

 W_{α} note that it is possible for moving droplets to exhibit it is possible for α $n \cdot \mathbf{A}$ and $\mathbf{f}_{\text{max}} \in \mathbb{R}$, $\mathbf{A} = \frac{1}{2} \times 0.17$ $\mathbf{A} = \frac{1}{2} \times 0.17$ Typical droplet with a restriction $\begin{array}{l} \mathbf{f} = \mathbf{f} = \mathbf{1}, \mathbf{g}, \mathbf{f} = \mathbf{g}, \mathbf{g},$ $\sum_{\alpha\in\mathcal{A}}\frac{1}{\alpha} \left(\begin{array}{cc} \alpha & \alpha & \alpha \\ \alpha & \alpha & \alpha \end{array} \right) \left(\begin{array}{cc} \alpha & \alpha & \alpha \\ \alpha & \alpha & \alpha \end{array} \right) \left(\begin{array}{cc} \alpha & \alpha & \alpha \\ \alpha & \alpha & \alpha \end{array} \right) \left(\begin{array}{cc} \alpha & \alpha & \alpha \\ \alpha & \alpha & \alpha \end{array} \right) \left(\begin{array}{cc} \alpha & \alpha & \alpha \\ \alpha & \alpha & \alpha \end{array} \right) \left(\begin{array}{cc} \alpha & \alpha & \alpha \\ \alpha & \alpha$ bubbles, which have received a great deal of attention in the $\mathfrak{t} = \frac{1}{20} \frac{\mathfrak{N}}{H} \mathfrak{r}$. 20 However, typical bubbles are much larger. With the much larger sizes are much larger. With the much larger inclusion of non-local magnetostatic fields, Γ that a static bubble will be static bubble for a $55 - 10$ and with a $\sqrt{5}$ $r\partial_t$ and $63\,\mu$. Thus, droplets can be viewed as smaller, ∂_{μ} dynamic generalizations of the static bubble \mathbf{g} A l $\sqrt{\gamma}$ and $\sqrt{\gamma}$ and a slowly variable γ and γ and γ and γ

 m_{α} is the set of $|h_0|$, $|h_0|$ is the restriction of the n restriction on the h_0 restriction on the h_0 $m\in \mathbb{R}$, can spin, h_0 , causes the total spin, momentum, and h_0 , and h_1 e_n energy to evolve in time. The map to Γ (*w*, *V*), we can be Γ from f assumed to be nucleated assumed 300 nm from the nucleated 300 nm from the nucleated 500 $c^*_{\mathcal{P}}(z) = \mathbf{f}^*_{\mathcal{P}}(z) + \mathbf{f}^*\mathbf{v}^{-1} +$ reaching the second wire or unit the soliton center or unit \mathcal{H}^{\bullet} or unit \mathcal{H}^{\bullet} or unit the soliton center of \mathcal{H}^{\bullet} at the value $m_z = 0.5$. For the model case ℓ the model case of ℓ $= 0.01, \quad t \rightarrow \infty$ **is predicted to the 3** μ in a μ 30° for a 15-ma current in each wire with a 3.3 - μ with a μ \mathcal{S}_s and \mathcal{S}_s approach 600 m/s. In the low-loss can approach 600 m/s. In the low-loss can approximate \mathcal{S}_s and \mathcal{S}_s a case = 0.001 , the droplet can propagate about $10 \mu^2$ in 70° for 10 -ma current with a 10.3- μ wire separation.

C. \therefore \therefore \therefore \therefore \therefore \forall $\frac{1}{\sqrt{h_0}}$ $\alpha \ll 1$

The regime, $r = \frac{1}{2} \oint_C \mathbf{r} \cdot d\mathbf{r}$, $\sqrt{\frac{1}{2}} \oint_C \frac{d\mathbf{r}}{d\mathbf{r}} = \frac{1}{2} \int_C \mathbf{r} \cdot d\mathbf{r}$, $\sqrt{\frac{1}{2}} \oint_C \frac{d\mathbf{r}}{d\mathbf{r}} = \frac{1}{2} \int_C \mathbf{r} \cdot d\mathbf{r}$ $\begin{array}{c} \Psi_1,\ldots,\Psi_{n-1},\ \Psi_2,\ldots,\Psi_{n-1},\ \Phi_3,\ldots,\Phi_{n-1},\ldots,\Phi_{n-1},\ldots,\Phi_{n-1},\Phi_4,\ldots,\Phi_{n-1},\ldots,\Phi_{n-1},\ \Phi_4,\ldots,\Phi_{n-1},\Phi_5,\ldots,\Phi_{n-1},\Phi_6,\ldots,\Phi_{n-1},\Phi_7,\ldots,\Phi_{n-1},\Phi_8,\ldots,\Phi_{n-1},\Phi_9,\ldots,\Phi_{n-1},\Phi_{n-1},\ldots,\Phi_{n-1},\Phi_{n-1},\ldots,\Phi_{n-1},\Phi_{n-1$ magnetic field, assuming that a propagation of the angle \mathcal{L} created. In Fig. 3, solution of the modulation (3) reveals \mathbf{B}_l , 3, $\frac{1}{2}$ \mathbf{C}_l \mathbf{A}_l \mathbf{A}_l α , \mathbf{y} , \mathbf{y} is 0 or positive. When \mathbf{y} is 0 or positive. When the field is sufficiently negative, the droplet can experience can expe deceleration and then acceleration as its amplitude decays. T) and complete deroplet acceleration due to damping was derived as \mathcal{L} , where the damping was derived was derived was defined as \mathcal{L} predicted for $\mathbf{1D}$ drops in the absence of a magnetic field. $\mathbf{23}$ \mathbf{W}_{α} , where \mathbf{y}_{α} is behavior in terms of the droplettic in terms of the droplettic theorem effective mass [\(5\).](#page-2-0) From Eq. [\(5\)](#page-2-0) ζ is $P = m_{\tilde{m}}V + m_{\tilde{m}}V$, $\mathcal{T} = \mathcal{T} \circ \mathcal{D} = \mathcal{D} = \mathcal{D}$ and $\mathcal{D} = \mathcal{D} = \mathcal{D} = \mathcal{D} = \mathcal{D}$ field absolute $g^2 = \frac{1}{2} \int_{0}^{1} \mathbf{E}_a \cdot (\mathbf{3} \cdot) \mathbf{F}_a \cdot (\mathbf{1} \cdot \mathbf{B})$ in $\mathbf{F}_a = \mathbf{0} \int_{0}^{1} \mathbf{F}_a \cdot (\mathbf{0} \cdot \mathbf{B})$ t_{α} , $\sum_{i=1}^{n}$ if $\sum_{$

$$
\hat{m}_{\text{ff}} < \hat{P}/V < 0. \tag{6}
$$

 $\mathbf{I} = \mathbf{I} \times \mathbf{V}$ of the system is accelerated in the presence in the p of damping because the effective mass is decreasing at a set $\mathbf{f}:\mathbf{M} \rightarrow \mathbf{f}$

As the examples in Figs. 3(c) and 3(e) suggests in \mathcal{A} (6) **f s** \therefore **w** \therefore **w** \therefore **w** \therefore **w** \therefore **d**₁ **c** \therefore **h**⁰ *<* $0,$ there are some droplets that exhibit deceleration. In this term of the deceleration. In this case of \mathbb{R} case, the magnet appears to undergo a complete reversal to the $(V, \alpha) = (0,0)$ state for $\beta \downarrow \beta$ in the parameters β in β in the parameters β in β in β in β \mathbb{R}^n and \mathbb{R}^n and \mathbb{R}^n and \mathbb{R}^n are \mathbb{R}^n in the *switching separatrix* $T = \sqrt{-1}$ \therefore $\frac{1}{2}$ to the stable stable stable stable stable \therefore **h**₁(*i*) $f(x, \theta) = (0, -h_0)$. L_{inear}iation $f(x, \theta) = f(x, \theta)$ $\textbf{f} \cdot \textbf{E}$ (3)

